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THE INSTITUTE OF PETROLEUM.

An Ordinary General Meeting of the Institute of Petroleum was held at Manson House, 26 Portland Place, London, W.1, on Wednesday, March 9, 1949. Mr E. J. Sturgess, member of Council, was in the Chair.

The Minutes of the Ordinary General Meeting held on February 9, 1949, were read, confirmed, and signed, and the general secretary announced elections to membership since that meeting.

The Chairman, introducing the lecturer, Mr John Lamb, said: Mr Lamb published his first work on diesel engines as far back as 1919, and in 1947 he was awarded the Denny Gold Medal for the best paper read before the Institution of Marine Engineers in that year.

I think that the large audience we have here to-night reflects the general interest which will be taken in the paper. This modern trend in tanker development gives food for thought to all sections of the oil industry. And not only to the oil industry but also to harbour authorities and others. At the present moment there is a bill going through Parliament for extensions to the oil-dock at the entrance to the Manchester Ship Canal which have to be carried out in order to accommodate the much larger tankers which will be running in the near future. Apart from these problems there are more real problems in ship-to-shore facilities required to handle oil at the increased speeds which are proposed in the future. What that may mean can be realized when one knows that recently a 28,300-ton cargo of oil was loaded in the Persian Gulf through two under-sea lines, 12 in diameter and 6000 ft long, in 21 hr. It was discharged at its destination in 20 hr, and it sets quite a new standard in discharge facilities required at shore installations.

The following paper was then presented :—

THE MODERN TREND IN TANKER CONSTRUCTION.

By John Lamb, O.B.E.

As an ocean-going oil tanker is used for the transportation of liquid cargoes only, it has little in common with the general cargo ship as regards internal arrangement. The cargo spaces of tankers must be smaller to avoid excessive surging of the moveable cargo in a seaway, and double-bottom tanks over the whole length of the ship for the accommodation of ballast water are unnecessary, as the cargo spaces of a tanker are suitable for the carriage of water ballast in sufficient quantity to meet all conditions at sea. Furthermore, owing to the highly inflammable nature of many of the cargoes carried by tankers it is necessary to isolate the cargo spaces as far as possible, and consequently the propelling machinery is generally situated abaft the cargo space, from which it is separated by a dry space or cofferdam about three feet wide, which can be filled with water if necessary. This location for the machinery eliminates the propeller-shaft tunnel, which

is a potential source of danger when the machinery is situated amidships owing to the possibility of explosive gases reaching the boiler-room. A second cofferdam, forward of the cargo space, separates the cargo from the comparatively short forehold and forepeak in which dry cargo, fuel, and fresh water are usually carried.

A fully loaded dry-cargo ship is kept afloat mainly by the buoyancy of the machinery space situated about mid-length, while a tanker is supported at the ends. Thus, the sagging stresses are much greater in a tanker than in a dry-cargo ship with machinery situated amidships. As, however, the cargo hatches of a tanker are smaller and the closing plates proportionately stronger than the corresponding parts of a dry-cargo ship, the law permits deeper loading and a greater weight of cargo to be carried than is permissible in a dry-cargo ship of equal size. In practice the difference in freeboard for ships having a length of 460 ft by 59 ft beam is about 15 in, and the extra cargo carried by the tanker would be in the region of 850 tons. Because of this low freeboard, tankers must be provided with elevated fore and aft gangways to permit ready communication between the forecastle head, navigation bridge, and poop, the three positions necessary for the proper handling of a ship.

In order to reduce to a minimum the stresses produced in a tanker's hull during heavy weather, it is important that the loads, such as machinery, cargo, bunkers, fresh water, etc., be distributed as evenly as possible over the entire length of the ship. The cargo, which is the greatest load, should, therefore, be carried over the greatest possible proportion of the ship's length, but in order that a fully loaded ship will trim correctly the centre of gravity of the cargo space must have a fixed relation to the longitudinal centre of buoyancy of the ship, which is also the longitudinal centre of gravity of the ship's displacement. Having fixed the centre of the cargo space, the cubic capacity forward of this point must be equal to the cubic capacity abaft it, but as any limit to the cargo space abaft this point is determined by the required length of machinery space, it will be seen that the machinery space also limits the length of the cargo space forward of this point.

In designing the machinery space of Shell tankers, every consideration is given to the provision of naturally lighted, well-ventilated engine-rooms and adequate space for overhauling machinery. The Ministry of Transport also have these desirable features in mind, and as an incentive to ship-owners generally to make due provision they allow an appreciable reduction in the net tonnage of the ship if the capacity of the machinery space is not less than 13 per cent of the gross tonnage. The minimum length of the machinery space is, therefore, decided by these considerations, and this really determines the maximum permissible length of the cargo space.

Having fixed the total length of the cargo space, the next step is to divide it into a number of compartments by means of oil-tight transverse bulkheads at intervals of from 30 to 40 ft, the actual spacing being determined by various factors. Two oil-tight longitudinal bulkheads spaced about 20 per cent of the ship's breadth each side of the centre line and running the full length of the cargo space subdivide these compartments into port, centre, and starboard tanks. The hull of a tanker comprises, therefore, a forepeak, forehold, forward cofferdam, a number of cargo tanks each divided into three

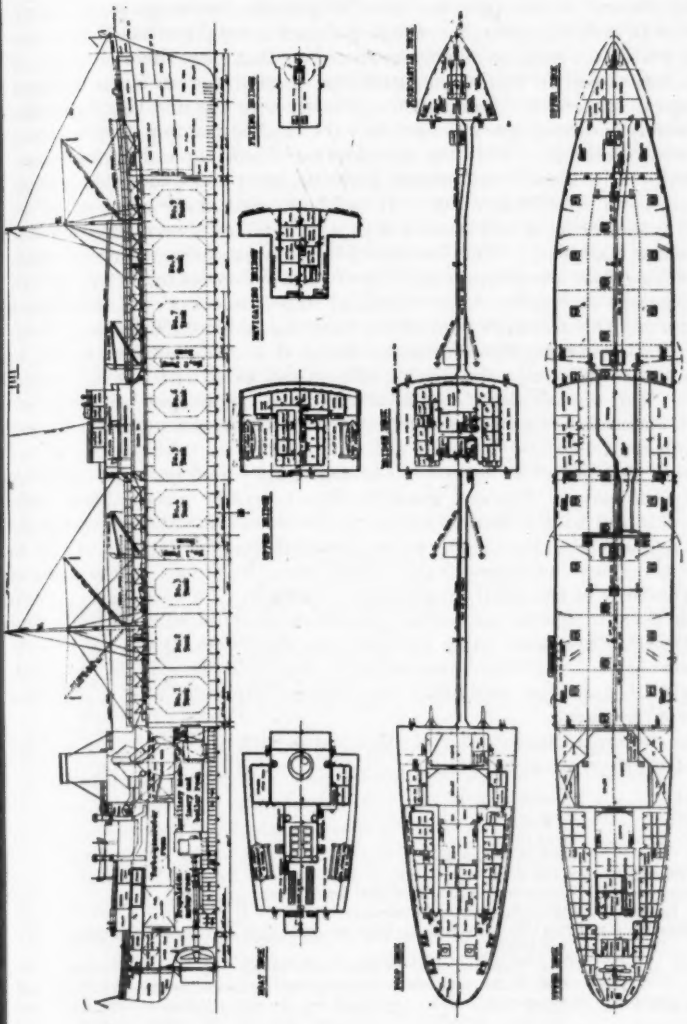


FIG. 1.

GENERAL ARRANGEMENT OF *HELICINA* AND *HYALINA*.

compartments, pump-room, after cofferdam, machinery space, and an after peak.

The practice in the past has been to provide two cargo pump-rooms, situated in such a position that the cargo space is roughly divided into three equal portions. Such an arrangement ensures that three different grades of cargo can be carried without slightest fear of admixture so far as bulkhead leakage is concerned. Pump-rooms situated near the mid-length position also act as buoyancy spaces and reduce the sagging bending moment under full load conditions. With the introduction of welding and improvements generally in bulkhead construction, however, one pump-room only is likely to be general practice in future. It will be located at the after end of the cargo space, where it will also serve as a cofferdam between the cargo and propelling machinery. This location of the pump-room has other important advantages from the operational point of view. For instance, if steam-driven cargo pumps are employed, the lengths of large diameter steam and exhaust pipes along the decks are eliminated, resulting in more efficient use of the steam and lower maintenance costs, whilst if electric motors are used to drive the cargo pumps the driving motors can be situated in the engine-room. This applies also if steam-turbine drive is employed, in which case the steam need not leave the machinery space and can be used to the greatest advantage.

As an example of an up-to-date tanker a brief description of the sister ships *Helicina* and *Hyalina*, shown in Fig. 1, will be given. These ships were designed by the Marine Technical Division of the Shell Group as far back as 1942, but the design was so advanced that few tankers, if any, to equal them have since been built. They were the answer to the desire of the Directors of the Shell Group to build tankers of a speed which would enable them to operate unescorted and which would be suitable for fuelling the British Fleet, then being assembled in the Pacific Ocean for the war against Japan. Actually three ships of this class were built; the first, namely, H.M.S. *Olna*, was taken over by the Admiralty and is still being operated by them.

The principal dimensions and other particulars of the *Helicina* and her two sister ships are as follows :—

Length . .	550 ft 0 in B.P.
Breadth .	70 ft 0 in moulded.
Depth . .	40 ft 6 in ,,
Draft . .	31 ft 9 in L.S.M.
Deadweight .	18,176 tons.
Framing .	Combined longitudinal and transverse.
Cargo tanks .	27 separate oil-tight compartments.
Pipelines .	12 in dia and able to load or discharge four grades of cargo simultaneously.
Boilers . .	Three Babcock and Wilcox water-tube type, 425 lb pressure and 750° F temperature. Scotch-type auxiliary boiler, 180 lb pressure.
Cargo pumps .	Reciprocating type operated by de-superheated steam from main boilers. Auxiliary boiler used for fuel and cargo heating only.
Turbines .	Two multi-stage impulse type 3910–4150 r.p.m.
Alternators .	Two, each 4200–5000 kW, 3-phase, 3000 volts A.C.
Propeller .	Single 115/120 r.p.m.
Speed . .	17·5 knots trial, 16·5 knots service.

The arrangement of the turbo-electric machinery was such that in the event of the service speed of 16·5 knots not being required at some future

time, half the power-plant could be shut down and the remaining half operated on a flat efficiency curve to give the ship a speed of about 13 knots. Two turbo-alternators, each of 6500 s.h.p., supply current to a propulsion motor enclosed in one casing but comprising two independent units. Provision is also made to enable either unit of the propulsion motor to be supplied with electric current by either of the turbo-alternators, thus ensuring a high degree of reliability. This machinery arrangement also provided for the assumption that the internal-combustion turbine would be developed for marine propulsion and, in consequence, the possibility that at some future date one of the steam-driven turbo-alternators would require to be removed and replaced by an internal-combustion turbine, thus enabling experience to be gained with this new type of engine without jeopardizing the safety of such a large and costly ship.

A special feature of the *Helicina* and *Hyalina* is that the main boilers are capable of burning a waste product, at present known as cracked asphalt or bitumen. This fuel has a specific gravity of 1·06 at 60° F and a viscosity of 20,000 sec Red. I at 212° F. Experiments in burning this extremely viscous petroleum residue were carried out under the direction of Shell Group marine technicians, and the results ultimately obtained prove that such fuel can be burnt efficiently providing certain alterations are carried out to the standard oil-burning installations and adequate provision made to ensure that the fuel is maintained at a pumpable temperature under all likely conditions.

Other special features are :—

1. The ships are approximately 90 per cent welded construction.
2. The maximum cargo loading rate is 3000 tons an hour and the cargo discharge rate 1500 tons water per hour against a back pressure of 100 p.s.i.
3. The ship is capable of carrying all grades of liquid cargo, from the most viscous to the most volatile.
4. All officers are accommodated amidships, and the petty officers and crew aft.
5. Every member of the ship's company is provided with a separate, comfortably furnished cabin of not less than 80 sq. ft., the average floor area of all crew cabins being 90 sq. ft.
6. The petty officers, seamen, stewards, and firemen have separate messrooms, and men in the same departments are grouped together.
7. Petty officers are provided with a comfortably furnished and spacious smoke-room.

The *Helicina* was commissioned in October 1946, and the *Hyalina* in February 1948, and at no time has either ship had an involuntary stop at sea or been delayed in port for which the ship or its machinery could be held responsible. The average all-the-year speed is 16·5 knots on 11,000 s.h.p., and the fuel consumption for all purposes (including cargo heating) is 90 tons a day. In order to obtain certain information the *Helicina* made a round Atlantic voyage with one turbo-alternator only operating, and the 5,500 s.h.p. developed gave the ship an average speed of 13·6 knots, the daily fuel consumption for all purposes being 52·2 tons. This test illustrated very clearly how high is the price to be paid for speeds over 13·6 knots.

Until quite recently the most usual size for a deep-sea tanker was 12,000 tons deadweight with a service speed of from 11 to 12 knots. Drawing about 27 ft 6 in when loaded, such ships are the most economical for world-wide trading, and it will be a long time yet before these handy tankers become obsolete. The present demand for larger tankers arises partly from the greatly increased building costs and the higher operational costs. The larger the ship the lower is the building cost per deadweight ton and the less will be the cost to transport a given quantity of cargo over a given distance. As, however, the larger the ship the greater must be its loaded draft, its flexibility as regards the number of ports that can be served is correspondingly reduced. Until the depth of water at the berths and approaches used by tankers has materially increased, the proportion of tankers drawing 30 ft and over will be limited. If progress in this direction is not to be retarded, harbour authorities will have to provide improved facilities, since shipbuilding technique has already advanced to the stage when tankers up to 50,000 tons deadweight could be soundly constructed.

Calculations show that the most economical speed for a 12,000-ton D.W. tanker is still under 12 knots, if by economical speed is meant the lowest cost to carry a certain quantity of cargo a given distance. In calculating the economical speed for any given deadweight, various characteristics of the ship have to be taken into account, the most important being that of length on the water-line. Broadly speaking, as the length on the water-line increases, the service speed for minimum operating cost per ton of cargo carried also increases, so that the economical service speed for an 18,000-ton D.W. ship is about 13 knots and for a 28,000-ton ship 14 knots. While speeds in excess of the economical speed increase the quantity of cargo that can be transported in a given time, such speeds increase the power and consequently the fuel consumption very considerably, and the greater quantity of fuel that must be carried to meet the higher consumption shuts out a corresponding quantity of cargo. Moreover, such a ship, if to be suitable for all weathers, must be given finer lines, which not only reduces the deadweight but increases the building cost per deadweight ton.

Tanker Design.

The most notable development in tanker design during the last decade has been the universal adoption of twin longitudinal bulkheads in place of the summer tank and centre-line bulkhead arrangement. A typical midship section of a summer tankship is shown in Fig. 2. The summer tanks extend longitudinally between the main and upper decks for the whole length of the cargo space, and their size and location provide an expansion trunk for the main tanks. As the name implies, the summer tanks were used for the carriage of cargo during fine weather periods only, when it is permissible by law for a ship to be loaded more deeply than during winter months. Furthermore, tankers are designed to reach their fully loaded draft when all cargo spaces are filled with low-gravity (50 cu ft per ton) cargo, so that when high-gravity cargoes have to be carried a ship would be down to her marks before all cargo spaces are filled. This would mean that either the weight distribution would be unsatisfactory and subject the ship to undue strains when in a seaway, or the tanks would contain liquid

having a large free surface, which besides over-stressing the bulkheads would make a most uncomfortable ship in bad weather. From these brief remarks and an examination of Fig. 2, the reasoning behind the summer tank form of construction will no doubt be clearly understood.

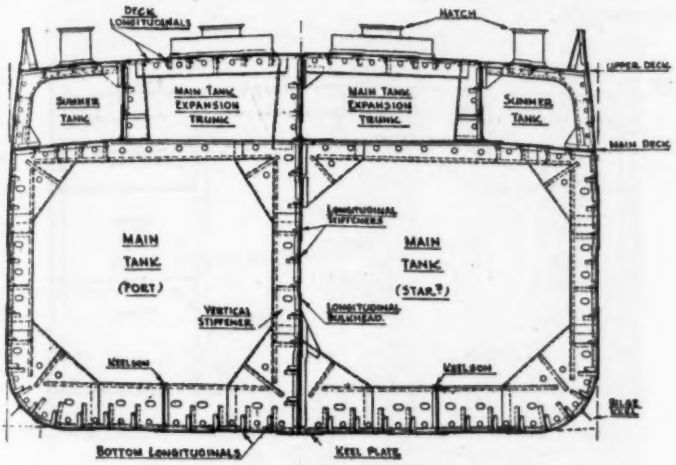


FIG. 2.

MIDSHIP SECTION OF A SUMMER TANKSHIP, LOOKING FORWARD.

The summer-tank type of tanker was abandoned because of the expense incurred in keeping the floors and inner bulkheads of the summer tanks fluid-tight, and the necessity to gas-free such tanks together with the main tanks irrespective of whether they were being used for cargo or not. Moreover, owing to their location the outer surfaces of the inboard side and bottom of summer tanks corroded at a greater rate than the remainder of the structure.

A typical midship section of a twin longitudinal bulkhead tanker is shown in Fig. 3. These bulkheads, like the transverse bulkheads, are made oil-tight, and it will be seen that in addition to serving as principal strength members, they divide the cargo space longitudinally into a centre compartment and two wing compartments. The bulkheads are situated an equal distance from the centre line, and the spacing generally results in each of the wing compartments being smaller than the centre compartment. The principal factors which determine the spacing of the longitudinal bulkheads are strength and cargo flexibility. The system of ballasting to be adopted influences the location of the bulkheads also, but the spacing shown in Fig. 3 is for all practical purposes the most suitable and the one generally adopted. This spacing is the best for centre-compartment ballasting and makes for a comfortable ship when heavy weather is encountered during ballast voyages. In tankers built to carry bitumen the longitudinal bulkheads are spaced comparatively wide apart. The reason for this is that it is not good practice to put water ballast into compartments intended for

such cargo, and as such cargo must be maintained at a temperature of about 250° F, it should be, as far as possible, confined in spaces where it will not be subjected to the cooling effect of the sea. The wing compartments are, strictly speaking, ballast tanks only. The comparatively wide spacing of the longitudinal bulkheads in this class of tanker is also necessary to reach the deadweight.

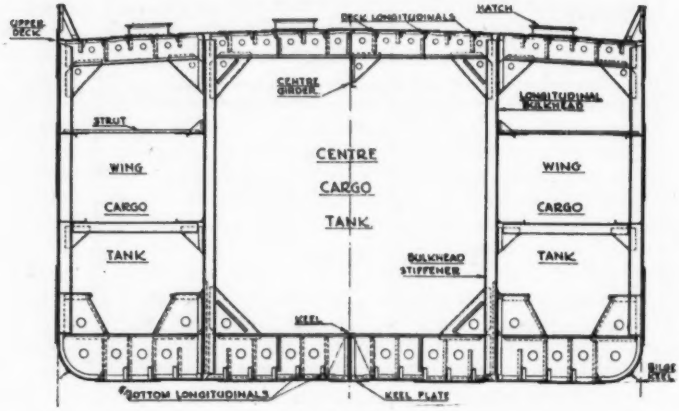


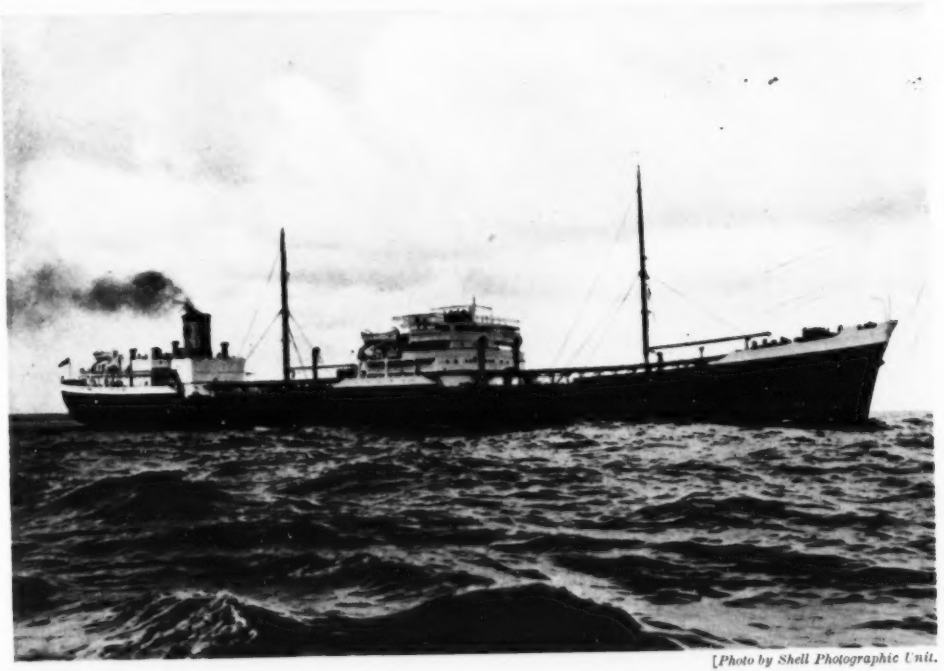
FIG. 3.

MIDSHIP SECTION OF A TWIN LONGITUDINAL BULKHEAD RIVETED SHIP, LOOKING FORWARD.

As already mentioned, the cargo space of tankers is further divided by a number of transverse bulkheads, the spacing of which is determined mainly by the desired degree of cargo flexibility. Comparatively wide spacing reduces the number of bulkheads required for a given length of ship and results in lower building costs, but longer tanks produce greater free-liquid surfaces and a higher degree of surging in a seaway, besides reducing the number of different grades that can be carried in a given size of ship. As a compromise, some favour long-wing compartments and comparatively short centre compartments, in which event there may be ten centre compartments and five wing compartments on each side.

The bulkheads of a tanker are a very important part of the structure, as not infrequently oils of widely different characteristics have to be carried with only bulkhead separation, and when a ship is pitching and rolling in a seaway, the stresses to which the various components of the structure are subjected are very severe. A tanker's hull, as well as the bulkheads which divide the cargo portion, must be of very sound construction if leakage or admixture of the different grades of oil is to be avoided.

Prior to the 1939 war, tankers generally were of all-riveted construction, although even at that time it was the practice of the Shell Group to weld parts other than the members which contributed to the longitudinal strength of the ship. The reason for this restriction was not because of doubt as to the strength of welding, but rather to the generally accepted view that



[Photo by Shell Photographic Unit.

T.E.S. "HELICINA," FLAGSHIP OF THE ANGLO-SAXON PETROLEUM FLEET.

[To face p. 288.

RECREATION ON THE T.E.S. "HELICINA."

(*Above*). A cross shot of the officers' smoke-room and, on the opposite page (*top*), a corner view of the petty officers' smoke-room, with (*bottom*) the crew's messroom. In this room a sliding bulkhead (seen open) which forms two messrooms when closed or a large recreation-room when open.

SLEEPING QUARTERS IN THE T.E.S. "HELICINA" FOR PETTY OFFICERS (*above*) AND RATINGS (*below*).

riveted construction allowed a ship to "breathe," giving the measure of flexibility necessary to reduce local stress. The results of recent research, however, have proved otherwise, and it can now be said that as far as flexibility and the avoidance of severe local stressing is concerned there is practically no difference between riveted and welded construction. A midship section of an all-welded tanker is shown in Fig. 4.

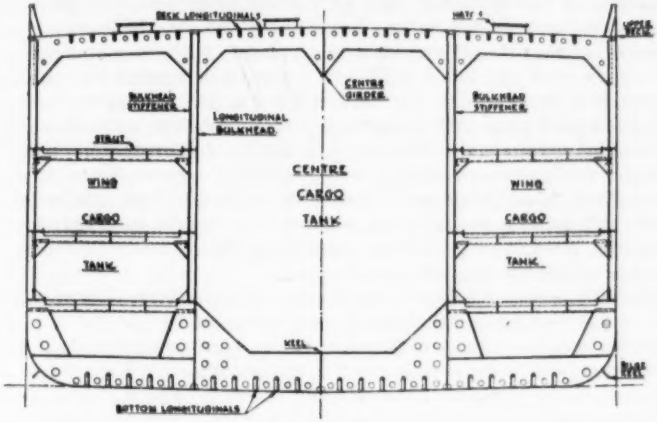


FIG. 4.

MIDSHIP SECTION OF AN ALL-WELDED SHIP, LOOKING FORWARD.

From the point of view of oil-tightness a properly welded joint is to be preferred to one that is properly riveted. Even to the uninitiated it must seem wrong to punch rows of holes in shell plates and fill them up with rivets, thus producing a host of potential sources of leakage. As regards strength there is nothing to choose between welded and riveted construction, but a badly welded connexion may have more serious consequences than a badly riveted connexion, and more careful supervision of welded ships is therefore necessary. During recent years considerable progress has been made in the technique of welded construction, and the position to-day is that practically all shipyards and repair establishments are equipped for welded construction, and the Shell Group have now several tankers in service which are practically of all-welded construction.

As regards the strength of a ship as a whole, the International Loadline Convention lays down a minimum standard, while the various classification societies have their own minimum standards for all component parts of the structure. These requirements apply to all tankers, but some owners, including the Shell Group, as a result of experience, keep well above these minimum requirements, chiefly in way of the cargo spaces, in order to provide a reasonable margin for corrosion.

CORROSION.

Corrosion in the cargo spaces of tankers is a very serious problem, as will be appreciated when it is stated that to renew the bulkheads of a 12,000-ton

D.W. ship costs about £180,000 and loss of about six months' trading, and that this may become necessary after only seven years in service. Corrosion has always been a matter for concern, but the problem has become much more serious of late. It is a fact that the rate of corrosion is much greater in tankers built since 1939 than in those built prior to that date, and the reason is as yet rather obscure, since the physical and chemical properties of the materials used have not altered. It may be that the great need for increased output has induced the steel mills to vary their practices, or that the shorter time which elapses between plates and angles leaving the mill and being built into a ship is detrimental to the lasting properties of the material. Most authorities will no doubt agree that a well-weathered steel plate will, if thoroughly cleaned before painting, resist the corrosive elements better than a plate not so well matured. Until non-corrosive steels are much cheaper than at present or means found to provide the surfaces of ordinary mild steel with an impervious skin which will remain indefinitely, the only course open is to apply a good anti-corrosion paint and renew the protective paint periodically before the bare steel becomes exposed to the corrosive elements.

Generally speaking corrosion begins at a comparatively slow rate, due to the resistance of the relatively hard outer surface of the steel plating. When this outer skin has been penetrated, however, corrosion proceeds at a much greater rate, and an important point in this connexion is that the continued reduction in the thickness of the plating causes it to be subjected to ever-increasing local stress, which has the effect of accelerating the rate of corrosion. Eventually the material becomes over-stressed, resulting in fatigue and fracture.

While corrosion of the outer surfaces of the shell plating of a tanker gives some of us cause for concern, the rate of wastage cannot be compared with that on the inner surfaces. Nevertheless, while the corrosion of the surface in contact with the sea is gradual it is very undesirable, since it results in a rougher surface and an increase in the resistance to motion. In the case of a 12,000-ton D.W. ship the loss in profit over a period of twenty years due to this increased skin resistance is in the region of £100,000. Considerable thought is now being given to this problem, and all I would say at present is that the results so far obtained by the Marine Research Department of the Shell Group are encouraging.

Loading and Discharge Rates.

The cost to build tankers and the cost to transport petroleum products, which are so essential to our civilization, have risen so much since pre-war, the approximate increase in each case being over 150 per cent, that tankers must spend a far greater proportion of their time at sea than is the case at present if these extra costs are not to be permanently included in the price to be paid by the consumer of the products carried. This means that cargo loading and discharge rates must go up, and whilst little more in this direction can be done on existing tankers, there is no doubt that tankers of the future will be capable of discharging at rates in the region of 1000 tons water per hour. In the case of existing tankers discharge of cargo would in many instances be expedited if the back pressure on a ship's pumps was reduced by

the employment of booster pumps on shore. Also, where viscous cargoes must be pumped through great distances in cold weather, the shore lines should be effectively lagged to reduce the drop in temperature between the ship and shore tank.

A weak link between ship and shore is the flexible hose almost universally employed to connect the ship and shore lines. These hoses generally limit the discharge pressure when new to 100 p.s.i., and as low as 70 p.s.i. before being taken out of service. If the turn-round of tankers is to be speeded up as circumstances demand, the maximum permissible pressure on the pipe-line should not be less than 200 p.s.i.

Not only will the rate of loading and discharging have to be greatly increased but the causes of delays preceding and following these operations will have to be eliminated. Many of the delays are due to the inflammable nature of certain cargoes and the necessity to take precautions. In most instances the precautions are fully justified, and no one who has seen a fully manned tanker on fire would advocate relaxation of restrictions if by so doing greater risk to life and property results. On the other hand, one can be over-cautious. For instance, it is unwise, as a general rule, to permit naked lights on a tanker loading a spirit cargo, and unreasonable to prohibit the use of such lights when discharging and the risks not so great. The risk involved during either operation varies in different ships owing not only to differences in construction and condition but to procedure followed by the ship's personnel.

If the principal causes of port delays are to be eliminated it must be safe to use naked lights at all times in certain parts of tankers. Nowadays seamen are disinclined to walk great distances in all weathers to cook meals or to smoke. Much discontent is caused thereby, owing to the food being served cold or nearly so, and as it would be positively dangerous in present-day tankers to allow smoking in accommodation or fires in galleys under certain conditions, the tanker of the future must be designed in such a way that petroleum gases cannot in normal circumstances leave the cargo tanks and spread along the decks. Should this occur the gases must be prevented from reaching the spaces where naked lights are necessary for the working of the ship. Tanks loaded with volatile oil should remain hermetically sealed until the cargo has been discharged and the petroleum gases expelled. The only exit for the gases should be through the venting system, provided on all modern tankers. This means that new methods must be found to take ullages and draw off samples. As mentioned later, it is no longer necessary to uncover openings in the deck to gas-free a tank, so that if provision can be made for sounding and sampling, explosive gas would be prevented from reaching the decks. A tanker would then be as safe as a dry-cargo ship, and the need for the precautions which extend the time in port to beyond that required to load or discharge the cargo would no longer exist.

If the ship's boilers are to be used during the loading and discharging of low-flash cargoes, sparks from the funnel introduce a hazard to shore installations. There are many forms of spark arresters and some will doubtless disagree with the statement that a really effective and practicable spark arrester for ship's funnels has yet to be produced. The problem is not so easy to solve as would appear, as not only must the particles of soot be cooled below their ignition point, but when extinguished the soot must be removed

from the path of the high-temperature gases passing up the funnel, otherwise portions of it may be re-ignited and be emitted from the funnel as sparks. Steam, next to water, is the most effective spark extinguisher, and the solution to this particular problem seems to be the elimination of the serious objection to the liberation of steam inside a ship's funnel.

Cargo Heating.

The heating of viscous cargoes to a sufficiently high temperature to ensure the discharge rate being no less than with low-gravity cargoes has been given much attention by the Marine Research Department of the Shell Group during recent years, and greatly improved results may be expected in future. This problem involved the prevention of rapid corrosion of the heating coils and the more economical use of heating steam. The wastage of steel coils was so great that their average life was very short, and it frequently happened that some part of the coils gave out when the tanks contained cargo, with the result that the ship arrived at her destination with the cargo insufficiently heated. Moreover, owing to the formation of corrosion scale on the coils the steam consumption tended to increase, and in motor-ships, where the boiler installation is of relatively small capacity, the reduction in heat transfer was in no small measure responsible for ships arriving with insufficiently heated cargoes. The seriousness of this problem will perhaps be more fully appreciated when it is stated that the present cost of renewing the heating coils in a tanker of 12,000 tons deadweight is in the region of £14,000.

The obvious solution to this problem was the substitution of stainless steel for mild steel, but the cost was, of course, prohibitive. The next obvious choice was cast iron, but coils made of such material would require to be much thicker than steel in order to withstand the internal steam pressure and would, in consequence, have a greatly increased weight, besides radiating less heat per unit area than the much thinner steel coils. Cast iron, however, was the only corrosion-resistant material in the economic range, and it was decided to adopt this material and design the coils in such a way that the greater weight and cost was offset by more efficient heat transfer. There was also to be considered the greater rigidity of cast iron and the liability of such coils to break when laid and secured in a tanker, which is of necessity a somewhat flexible structure.

These problems were systematically tackled and after a period of three years an entirely new type of heating coil for the cargo spaces of oil tankers has been evolved. They will last indefinitely, and as they do not produce corrosion scale they are uniformly efficient throughout the life of the ship into which they are fitted. During these experiments much useful information regarding the economical use of heating steam was collated, and when the application for patent rights has been negotiated all information regarding this successful investigation will be disclosed.

Gas Removal from Tanks.

Although ships have been carrying petroleum in bulk for over fifty years, surprisingly little ordered thought has been given to the important question

of positively removing the dangerous gas after discharge of volatile cargoes. This is a very necessary part of tanker operation, since at some time during the ballast voyage men must enter the cargo spaces to remove sediment and attend to fittings. Also, it is good practice to gas-free a tanker as soon as possible after discharge of low-flash cargo, as before this is done the ship is in an unsafe condition, and in the event of a collision or grounding the consequences may be much more serious because of the presence of petroleum gas in the cargo spaces.

As will be appreciated, the main consideration in tanker design is strength to resist the elements. This involves heavy framing and the provision of numerous strength members, all of which for obvious reasons must be situated within the ship. Such a form of construction makes it difficult to avoid pockets where heavier-than-air gas will collect, and as expulsion of the gas must take place at the top of tanks, the gas-freeing of a ship's cargo tank cannot be compared with gas-freeing a shore storage tank. The means at present employed to expel the gas from ships' cargo tanks is to rig windsails, inject steam, employ Butterworth machines, or gas ejectors. The effectiveness of windsails depends entirely upon the force of the wind, which is often nil when required, and while steam injection is effective it is undoubtedly responsible for much of the corrosion that occurs inside the tanks. The Butterworth machines are said to be effective, but they must be rigged when the tank is in a highly dangerous condition, and the utmost care must therefore be exercised when doing so to avoid producing a spark.

The marine technicians of the Shell Group began to tackle this problem some four years ago, the ultimate aim being to expel all petroleum gas independent of the state of the wind and without opening the tank in a way which would result in dangerous gas reaching the deck or any part of the ship. After numerous tests the steam gas ejector was considered the most promising means of expelling the gas, but the ejectors then used were very inefficient in relation to the quantity of steam consumed. Ultimately the efficiency of these ejectors was greatly increased, and although small enough to be easily handled by one man they are capable of expelling 35,000 cu ft of gas per hour, the petroleum gas being drawn through pipes extending to within a few inches of the tank bottom while the replace air enters the tank through the normal venting system. The practice in Shell tankers is to connect up and start one of these small ejectors as soon as the cargo has been discharged, and within 4 hr the tank is sufficiently free of gas to allow men to enter without gas helmets. The time required to gas-free a tank of 27,000 cu ft varies according to the amount of scale adhering to the sides of the tank. It is not now left to the mate's sense of smell to determine if a tank is free of petroleum gases and safe for men to enter for the purpose of mopping-up. Too many accidents have occurred as a result of this crude method, and Shell tankers are provided with instruments called "Pilot Explosimeters" which register instantly and accurately the ratio of air to petroleum gas, the dial of this instrument indicating clearly if the contents of a tank is explosive, highly toxic, slightly toxic, or clear.

The following are records taken at random of two tests carried out after discharge of aviation spirit. In the first the tank was practically free from scale and all petroleum gas was expelled in 1 hr 40 min. In the second case

the walls of the tank were almost uniformly covered by $\frac{3}{16}$-in-thick scale and the time to gas-free was 4 hr.

Time.	Explosimeter readings at—		
	10 ft.	25 ft.	40 ft.
T.E.S. Hyalina—*Tank No.* 2 *Starboard*—*June* 28, 1948.			
12.20 p.m.	12	30	100
12.50 „	5	15	44
1.10 „	0	5	10
1.40 „	0	0	2
2.00 „	0	0	0
M.S. Taria—*Tank No.* 10 *Port*—*May* 5, 1948.			
2.00 p.m.	90	100	100
2.30 „	50	90	100
3.00 „	20	60	80
4.00 „	8	45	60
4.30 „	0	18	20
5.00 „	0	8	18
5.30 „	0	0	8
6.00 „	0	0	0

The gas ejectors used are so effective that as soon as zero reading in the explosimeter is obtained, men may safely enter the tank without masks and begin mopping-up, providing the gas ejectors are kept operating. Where the surfaces of the tanks are covered with corrosion scale which absorbs spirit and releases it gradually in the form of gas after the liquid has been discharged, it is advisable to test the contents again if men are required to enter the tank after the gas ejectors have been shut off.

Propulsion Engines.

Prior to the war the vast majority of tankers constructed in the U.K. were of 12,000 tons D.W. and provided with slow-running direct-coupled diesel engines which gave a speed of about 12 knots. For war purposes larger and faster tankers would have been more suitable, but as the need for more ships in the shortest time was of greater importance, the type of tanker turned out was very similar to the pre-war product. Manufacturing facilities were already available for the construction of such ships and to have made a wholesale switch-over to another type would have reduced the output of the shipyards for a time, which in the light of experience would have proved disastrous.

For our American friends the position was very different. To meet their commitments new shipyards had to be laid down, and as space was not a factor to be considered (as in the U.K., where in some instances the plating of a ship on the stocks shuts off daylight from the dwelling houses in the vicinity), constructional facilities did not limit the size of ships to be built. As regards the type of machinery to be adopted, the equipment to turn out diesel engines on a large scale was not available, nor did they have the machines required to cut the reduction gears for geared-turbine installations. The outcome of this was that the propelling machinery decided upon was of

the steam turbo-electric type, which was the natural selection since the large up-to-date engineering works normally manufacturing land power installations could be easily and quickly adapted for the construction of ships' propelling machinery. Those of us who have first-hand knowledge of the renowned T.2 tankers know with what success our American friends accomplished what they set out to do.

This briefly is the reason why such ships were comparatively large and fitted with turbo-electric machinery, while in the U.K. we continued to build something which was considered by some to be inferior. This also explains why the American-built tankers are faster and have a comparatively high cargo pumping rate.

The few new designs that were evolved in the U.K. during the war were larger and faster, the limit reached being the *Helicina* and her sister ships, which were larger and faster than the American T.2 tankers. These increases in size and speed, however, were influenced by national requirements rather than by reasons of economy. Immediately following the conclusion of hostilities the need was to replace our enormous war losses, and the building of tankers for which the yards were best equipped continued.

The diesel engine directly coupled to the propeller shaft is still the most popular in powers within its practical range, because of its substantial advantage over steam-driven machinery in the matter of fuel consumption for a given power developed. Just how long this type of engine will retain its popularity it is difficult to say, but it is fairly safe to predict that if it is to survive its fuel flexibility will have to be increased. Gone are the days when we could afford to feed marine engines with high-grade distilled petroleum. Nor is this necessary, as has been conclusively proved during the past few years.

Boiler Fuel for Diesel Engines.

Prior to the practical demonstration in Shell Group ships that it is possible to obtain the same thermal and physical results with medium viscosity boiler fuel as with comparatively costly diesel fuel, all motor-ships operated on the latter fuel. It is true that scraps of information about certain British and foreign-owned motor-ships operating on heavy fuel were circulated, but there was a noticeable reluctance to tell the world how it was accomplished and with what results, and one could only assume that the results were far from satisfactory. However, the first full and authentic account of a serious endeavour to solve this age-old problem and burn commonly used boiler fuels in marine diesel engines was given to the Institute of Marine Engineers, London, in December 1947,* and since that time many motor-ships have been converted and are operating satisfactorily on fuels which show an annual saving in fuel bill of more than £1500 per 1000 h.p.

The present position is that there is no reason whatsoever why four-cycle-type engines should not be equipped to operate on 1500 sec Red. I. at 100° F fuel without raising operating costs by one penny, especially as the cost to

* Lamb, John. "The Burning of Boiler Fuel in Diesel Engines," *Trans. Inst. Mar. Eng.*, 1948, **60**, 1–25.

equip, *i.e.*, £5000, represents less than a year's saving in the fuel bill of a 4000-i.h.p. installation. The larger the power installation the sooner will the capital outlay be recovered. In the case of an 8000-i.h.p. installation the capital outlay is little more than that stated, and at present-day fuel prices the annual saving would be well over £12,000.

At the present time motor-ships are already operating with complete satisfaction—with emphasis on the complete for the benefit of the sceptics—on 1500 sec Red. I. at 100° F fuel, which is the only limitation imposed, and tests carried out during recent months indicate that probably before the end of 1949 this limiting viscosity will be raised to 3000 sec and ultimately to 6000 sec.

A peculiar feature associated with the burning of boiler fuels in marine diesel engines is that with diesel fuel, as is well known, the cylinder-liners wear in a tapered direction, the maximum wear being at the upper ends, whereas with boiler fuels the wear is more or less uniform throughout the length of the cylinder-liner. Moreover, it has been proved that the maximum wear when burning boiler fuels is not greater than when burning diesel fuel, the actual figures being 2·2 thousandths of an inch per 1000 hr.

When cylinder liners wear in a tapered direction severe conditions are imposed on the piston-rings owing to the rings having to follow the constantly varying diameter of the cylinder. Also, when new piston-rings are fitted into a tapered cylinder-liner the gap or end clearance must be governed by that necessary when the rings are in the lower or least worn part of the cylinder, and this means that when the rings are in the upper or high-pressure part of the cylinder they are less effective as a gas seal.

As the maximum wear rate is no greater when burning boiler fuels (and the present indications in the several Shell Group tankers operating on this fuel are that it is even less than when burning diesel fuel), this peculiar feature when burning boiler fuel is not undesirable, since it might well result in the piston-rings giving longer service and in a reduction in the amount of gas leaking past the piston-rings.

As to the cause of this unusual feature the following theory is put forward. With diesel fuels, cylinder-liner wear is mainly due to abrasion, but when sulphur-containing fuels are used a proportion of the enlargement may be due to corrosion. In the form of sulphurous fumes, which is the condition in the upper and hottest part of the cylinder, no detrimental effect will result from its presence, but when the expanded gases reach the lower and cooler end of the cylinder the SO_3 gas forms sulphuric acid (H_2SO_4), which condenses on and corrodes the lower part of the cylinder wall. Most of this corrosion will take place when the engine is stopped or operating at comparatively low working temperatures, such as when manœuvring in and out of port.

As fuel economy is still a very important consideration, the diesel engine will doubtless continue to be supreme in this respect for some time to come. In tankers, however, there are other equally important considerations, and as such ships become larger these become more important. For instance, the larger the ship, the larger must be the power-installation, and as the machinery must be situated at the after end, space is an important factor. Moreover, steam must be available in tankers to heat certain grades of cargo to pumpable temperatures and if, in addition, steam is necessary to operate

the cargo pumps of round about 1000-tons-per-hour capacity, the boiler installations must be much larger than those at present employed. As the capacity of the boiler installation increases, and consequently the cost and weight, the question whether it is economical to carry around the world plant which is in use for less than 5 per cent of the time a ship is in service must be considered. One solution would be to operate the cargo pumps electrically, the current being generated by high-speed diesel engines. If such engines could be operated on the cheaper grades of petroleum fuels similar to the slow-running propelling engines, the result would be a very attractive installation indeed. The present position is, however, that a normal type of diesel propelling engine of over 7000 b.h.p. introduces difficulties, and high-speed diesel engines capable of operating satisfactorily on boiler fuels are not yet available.

Much attention is being given at the present time to the production of prototype internal-combustion turbines for marine use both in the U.K. and abroad, and reports from the various centres suggest that we are not behind in the U.K. The great advantage of this type of power producer is that its thermal efficiency will approach, if not exceed in course of time, that of the reciprocating diesel engine, with a considerable reduction in the number of moving parts subject to wear and tear. The grade of fuel that the internal-combustion turbine will successfully consume has yet to be determined. It has already been proved that diesel fuel is suitable, but now that the reciprocating diesel engine can be operated satisfactorily on less expensive fuels, the turbine will have to operate on similar fuels if it is to become a serious competitor to the diesel engine.

Large tankers of between 20,000 and 30,000 tons D.W. are very much in the news to-day. The small ships in this range are to be propelled by direct-coupled diesel engines, and in the remainder geared steam turbines will be installed. The power output of the propelling machinery varies between 7000 and 12,000 h.p., and the ships' service speed between 13·5 and 15·5 knots. These tankers are mostly intended for a particular trade, and much effort and money must be expended on harbours, wharfs, and oil installations before ships of this size can be considered suitable for world-wide trading.

Discussion.

Mr A. Logan : For some time past the general tendency both in the U.K. and in the U.S.A. has been to design tankers to the maximum size permitted by the conditions at the ports and on the routes on which they operate. The depth and width of channel, tides, berthing conditions, shore storage, and dry-docking facilities are all factors to be considered, and thus the practice is to select the maximum permissible draft and design the ship accordingly. As an example, I quote our 28,000-ton-deadweight ships now under construction in the U.K. and in the U.S.A. These ships will carry crude from the Persian Gulf to Britain and will have a loaded draft of approximately 34 ft, length 640 ft, and a breadth of just over 80 ft.

I would now mention ships engaged on the Lake Maracaibo service. Whereas twenty years ago, vessels were constructed of 4000 tons deadweight on a loaded draft of 13½ ft, to-day, with the increased depth of water

at the bar, we are able to construct vessels of nearly 8000 tons with a draft of 18½ ft. When I mention that the 28,000-ton ship carries the same number of staff and crew as our standard 12,000- and 15,000-ton ships, and that our new large lake tankers carry the same number of men as the 4000-ton ship, it will be appreciated that our recent tanker designs are aiming at reducing the operating cost per ton of cargo carried.

Reference is made in the paper to ships designed for the carriage of special cargoes. Mr Lamb mentions the special construction of ships for the bitumen trade, where adequate heating arrangements are fitted in the cargo tanks and where, to ensure that there will be no water entry into the cargo spaces, ballast is carried in separate tanks on the voyage back to the loading terminal.

One ship within the last twelve months has delivered about 160,000 tons of bitumen and 40,000 tons of fuel oil.

From such ships, with their heavy viscous cargoes, I turn to vessels operating in the carriage of liquid gases such as butane and propane. These cargoes are carried in cylindrical tanks erected in the normal cargo holds, which spaces, in the case of our ships, are used for the carriage of fuel and diesel grades.

Mr Lamb draws your attention to corrosion in the cargo spaces of tankers. For those who are responsible for the maintenance of our ships it is a very serious problem. Only to-day I have been arranging for a ship to go to the repairers, and the weight of steel required to do the repairs will be 660 tons.

When discussing loading and discharging, Mr Lamb mentions that cargo-pumps in the ships will, in the future, in order to expedite discharge, deal with back pressures of 200 p.s.i. Such provision will no doubt be made, but I feel that the receiving facilities, for example, adequate size of pipe-lines, adequate steam jacketing of pipelines carrying viscous grades, and tankage wherever possible adjacent to the discharge berths, will all greatly assist in the rapid discharging of the tanker's cargo.

One reference was made by Mr Lamb to T.2 tankers. No doubt many of you will have seen these ships and will know what they did during the war years. They have been most successful, and our chief worry is that, due to corrosion, fracturing of the bulkhead plates is now taking place.

From the paper it will be appreciated that endeavours are being made to ensure that tankers will have a reasonable length of life, that they will be economical in service, and will operate with the minimum of delays in port.

CAPTAIN J. P. THOMSON said: It is most opportune that a paper such as this should be read before the Institute of Petroleum, because in years gone by we have seen progress in the petroleum industry unparalleled in any other industry. The technologists are always making fresh discoveries; their life seems to be one long routine of research.

It is rather more than thirty-five years since I joined my first tanker, and after thirty-five years close association with the industry I know less about it than when I started, because of the fresh discoveries. I recall the early days when we changed over from carrying black oil to clean oil. It was then only a question of colour, but to-day we have all kinds of x and y to enumerate the character and to tell us how to get the maximum power out of the material at hand.

In connexion with the increase in the size of tankers from 12,000 to 30,000 tons, I wonder whether this is justified. The quality of steel is about the same and the construction is similar, but I note that Mr Lamb suggests we can go to 50,000 tons.

I would like to know whether in these large vessels it is intended to arrange a pipeline so that there may be symmetrical distribution when discharging and loading, and also that ballast may be discharged from the centre tank while cargo is being loaded into the wing tanks and thus keep the vessel on an even keel.

I hope that with the advent of the large tanker something may be done along these lines.

We all used to find that longitudinal bulkheads caused the most trouble owing to leakage, but now that is a thing of the past and we can say that our longitudinal bulkheads are equally as good as the transverse bulkheads, and in future it is hoped we can regard that factor as having disappeared altogether.

My next point is that these large tankers should have twin screws. In our large ships of 20,000 tons I thought we had reached the limit for normal operation with single screw. When the first 28,000-tonners came over here I made some enquiries and found that the ship's line had been improved to such an extent that the captain could operate his ship as quickly and as well as I could operate my smaller single-screw vessel.

A feature in the new design of tankers is the corrugated bulkhead, horizontal stiffeners having been dispensed with. This will contribute to easier and better cleaning, so that the product may be delivered in the same good condition as received. It may also help to combat corrosion.

Mr Lamb had dealt with the question of heating the cargo, and twenty years ago we had the same problem of raising the temperature. On one voyage I had a chief engineer who could get the cargo up to 130° F without any trouble. I found his secret; it was taking advantage of the latent heat. He had a scheme of his own by which he took advantage of the latent heat by an arrangement fitted on the exhaust pipe. The next ship I joined we had the same trouble in heating the cargo. I told the chief engineer, and he said, " Rubbish, that is nonsense." It was not very long before I met my old friend and he came aboard for a chat. I introduced him to the chief engineer, and after that there was no difficulty in heating the cargo.

In connexion with the subject of discharging, first there is the question of the oil temperature and secondly the size of the shore pipelines. It has come home to us very forcibly since we have had the electric pump that it is actually only a question of the temperature of the oil and the diameter and length of the pipelines on shore which control the whole situation. If that is the case, then it seems to me that there are few ports that have adequate facilities to cope with the matter. Mr Lamb mentioned 200 lb pressure. Well, I know you can do it with a rotary pump, but with a plunger pump I think the pump would not last long, and an effort should therefore be made to give the ship the shore facilities she requires to discharge the cargo.

The question of gas freeing by using the ejector as soon as a tank is empty

has been raised. I quite appreciate the point, but I think a whole section should be emptied first.

Another point is valves, which have given trouble in years gone by. We have several improvements; an inspection flange at the bottom of the valve enables one to clean the valve, but that still does not meet the bill. I wonder if the day is not with us now when consideration should be given to designing a fool-proof block valve.

MR A. R. WILLIAMSON : My particular interest is in the certifying of tankers as gas-free and safe for any repair work—one point that interests me in the modern design of tankers is the proposal that pump-rooms should be just forward of the engine-room and that pumps may be driven by a shaft through the engine-room–pump-room bulkhead. I know one such case where a fractured pipe in the pump-room caused a flood of petrol in the pump-room and a disastrous explosion in the engine-room.

Another point which I have found causes difficulty is where the wing tanks are very long and in many cases have only one hatch. Such spaces are dark, difficult to gas-free and clean, particularly where the bottom transverse frames connecting the shell and bulkhead webs are high, and dirty cargoes (crude oil) or large quantities of scale can accumulate. Such tanks should have two hatches.

I am very interested to note that " everlasting " heating coils are a possibility. Fractured and choked heating coils are a continual source of anxiety when a ship is undergoing extensive repairs, as they often contain petrol or gas which cannot be blown out.

With regard to gas freeing of tankers, efficient ejectors are excellent, so are efficient windsails, but so often, on two bulkhead ships, windsails cannot be suitably rigged owing to lack of " skyhooks ". Special provision should be made such as samson posts or other facilities. It should be borne in mind that the Shipbuilding Regulations 1931 say that tanks shall be steamed.

Many tankers have various, almost inaccessible, spaces and in the event of a man being gassed or injured and unable to help himself there would be great difficulty in getting him out.

In conclusion, is there any possibility of tanker owners agreeing to number tanks uniformly either from forward or aft? As it is, some owners number from forward, and some from aft. Some have even numbers on the port side and odd numbers on the starboard. I have been on one ship (French) which was numbered from aft 1 to 7 on the port side and from forward 8 to 14 on the starboard side.

The particular system adopted may present no difficulties to the personnel of the ship, but dockyard people have to remember that while the ship in No. 1 dock is numbered from aft, that in No. 2 is numbered from forward. Failure to remember might be disastrous, and this has led to some narrow squeaks.

MR AXEL NORLING : Since Mr Lamb read his paper on the use of boiler fuel oil for diesels at the Institute of Marine Engineers in 1947, we have received many enquiries for the special separator equipment used on the *Auricula*.

I know of course that diesel engines had been running earlier on boiler

fuel, or at least that diesel manufacturers had claimed that this could be done, and remember especially an interview in 1918 with the chief engineer and designer of the Burmeister and Wain engines. He stated that their diesel engines were of such a design that they could run on any kind of fuel oil and did not require any cleaning apparatus either for fuel or lubricating oil. He soon changed his mind and included a clause in their general guarantee that both lubricating and fuel oil must be purified.

I also remembered that in 1925 and some years before the last war we had connexions with clients in other countries who were trying to run their diesels on boiler fuel oil. Nobody, however, pursued the matter like Mr Lamb has done or proved through long practical tests that removing not only the coarse and hard but also the fine abrasive impurities in the cheap boiler fuel oil reduced the wear on the diesel engine to not greater than that caused by using the more expensive diesel oil.

As Mr Lamb's tests have shown that the fuel consumption is about the same in both cases, this means that a big reduction in the running cost for all diesel-driven ships is possible.

Mr H. E. Skinner (Naval Construction Department, Admiralty) said : We are naturally always interested in what Mr Lamb says about tankers because he designed, or the Marine Division of the Shell Company designed, the *Olna* to which he refers, and I am happy to say that she has given us absolutely " trouble-free " service during the time that we have had her—like her sisters.

I would like to add the Admiralty's little bit to what has been said about the ever-increasing draft requirements of tankers. There is no doubt that we are going to have bigger and bigger tankers, and although, as one speaker said, we have gone up to 34 ft in draft, that is still too shallow, and we must get going and deepen our ports if these tankers are to be really successful. The deeper we can make our ships the less the stresses in the material, and that will help to solve this combined problem of the deterioration of the plates and the stresses on the structure.

Mr Lamb says there is nothing to choose between welding and riveting in construction. I think, as some one who deals in " eighths of an inch " instead of " thousandths," one ought to say that it is very necessary in connexion with welded construction that the design should be even better than in riveted construction because there is no chance of the welding slipping—which does take place in riveted construction—helping to spread the load more evenly on the remaining parts of the structure. So that if and when we come to completely welded construction we must have very careful design.

On the question of corrosion, Mr Rivett, in a recent paper to the Institution of Shipbuilders and Engineers in Scotland, advocated metal spraying as being a possible solution. I would like to ask Mr Lamb how he views that possible solution. Mr Rivett quotes the example of a tanker in his paper and says that a year after she had been metal sprayed there was no sign of corrosion in the holds.

In connexion with the discharge of cargoes Mr Lamb says the weak link is the flexible hose. He will be interested to know that the Admiralty have developed a flexible hose which will stand a pressure of 150 p.s.i. and has

been used at up to 200 lb. It is completely successful, and it has already been subject to a temporary pressure of 300 p.s.i. and has survived without any apparent damage.

The galley is a question which is worrying Mr Lamb, and it worried us too, because we are busy designing a tanker at the moment. Our friends in Lloyds Register have been a little kinder to us than to Mr Lamb, for they have allowed us to put the electric galley amidships.

Regarding the propulsion of large tankers, it seems as though the favourite method of propulsion will revert to turbines and the steam-ship. I would like to point out that in this striving after high efficiency we must not forget that there is a great deal to be done on the form of the ship and the propellers. It is possible to get a better economy in consumption by adjustments of ship form and propellers than by adjustments in machinery.

And finally, I ask Mr Lamb if he can tell us anything about the behaviour of *Auris*, which I believe is propelled by a large number of small diesel engines and a final electric drive.

MR F. G. VAN ASPEREN said: My firm was very pleased with the results obtained in *Auricula* with Werkspoor four-stroke underpiston supercharged engines without any modifications in the fuel-injection system.

Mr Lamb refers to this but only mentions the four-stroke engine equipped to operate on boiler fuel.

If I remember well he referred also to two-stroke engines with respect to the use of heavy fuels in his paper to the Institute of Marine Engineers.

Is there any reason for leaving this type of engine out now?

It may be pointed out that there are two-stroke engines which have proved to run satisfactorily on boiler fuel on the test bed, and this applies particularly to the new Werkspoor supercharged single-acting two-stroke engine.

It may be expected that in future ships equipped with two-stroke engines will give satisfying results in service when operated on boiler fuel, provided the fuel-injection system and the scavenging efficiency assure a perfect combustion.

MR STURGESS, the Chairman, closing the meeting said: I am sure you would excuse Mr Lamb for not answering the discussion now, as it is so late. His answers will appear in the Institute publication, and I hope anyone who has not been able to speak will write in so that we may have the benefit of his views.

I think you will all agree with me that it is a most absorbing subject, the fringe of which has only been touched on to-night. There are a lot more questions on the operating side; on the question of gas-freeing tanks which have contained leaded fuels, for instance. Mr Lamb will probably deal with that in his written reply. There are other points which I think are very much in our minds. A great deal of interest is being taken in the question of quick tanker turn-round, and there are, as those who come into contact with tankers know, a lot of human factors which delay ships turning round. There are the victualling problems, and the stores side, and if you ask the personnel to sail on a Saturday afternoon in Sydney there is probably an engine breakdown to prevent them. There are all these human factors which the theory of tanker turn-round does not always take into account.

However, the general economic questions which Mr Lamb has touched on are of absorbing interest not only to the oil industry but also to the harbour authorities as well.

I am sure you would like me to thank Mr Lamb on your behalf for a most interesting and instructive paper.

This concluded the meeting.

H. E. F. PRACY (written discussion) : There is one point which I should like raised, and that is in connexion with gas removal from tanks. The point which surprises me is that, after the gas has been removed and the explosimeter registers a zero reading, men are allowed to enter without gas-masks for the removal of sludge. I hope this does not apply to tanks which have been carrying leaded spirit. The regulations laid down by The Associated Ethyl Co. Ltd., for the cleaning of tanks which have contained leaded spirit, are extremely strict, and in no circumstances are persons allowed to enter the tanks without blower-type air-line gas-masks until all sludge and scale have been removed, and until the tanks can be certified not only gas-free but also lead-free.

MR H. MACKEGG (written discussion) : I would like to comment upon that part of the paper which deals with the use of boiler fuel oil for diesel engines, because I have had the privilege of co-operating with Mr Lamb in these experiments from the early days in some small way from the centrifuge point of view.

Mr Lamb refers to the people who, following upon the publication of his paper on " The burning of boiler fuels in marine diesel engines," have made claims that they have previously run their vessels on boiler oil. It is interesting to note that quite a number of these people, while giving very little information concerning wear rates, have been using fuel oil with viscosities well below 1000 sec Red. I at 100° F, which fuel oils have a Conradson value of 5 per cent, and a sulphur content of 1·5 per cent, whereas all the work which has been carried out in the Shell Group ships has been upon boiler oil with a viscosity of not less than 1500 sec Red. I at 100° F, having a Conradson value of 12 to 14 per cent and a sulphur content of 3 to 4 per cent; in fact, as Mr Lamb states, the only limitation put to their fuel-oil-supply people was that the fuel oil should not have a viscosity of more than 1500 sec Red. I.

A further point which I would like to emphasize is that the type of centrifugal separator plant employed in this work is a critical feature; in that it is essential that centrifugal purifiers and clarifiers be employed which have the highest constant separating efficiency, so that the throughput may be such that the *highest constant degree* of ash separation be maintained under all conditions. This constant result can be obtained only by using the largest disc-type centrifugal purifier bowl, so modified that the water seal will not break down, and at the same time that the bowl will have the maximum solid-holding capacity and self-discharging properties to enable the separators to be run for long periods without stoppages for cleaning.

These results have been achieved by the centrifugal separators which are employed in the vessels to which Mr Lamb refers. These are very im-

portant points, because the successful performance of the engine depends upon clean fuel oils, *e.g.*, fuel oil with a consistently low ash content, and the economics of the problem depend upon trouble-free operation with minimum attention. The work on this problem, which has so far been done by the De Laval organization, in co-operation with the Shell Group of vessels, clearly proves that shipowners would be well advised to carefully consider this question of the *correct fuel-oil-purification equipment* which would be installed in their vessels, because by installing the correct type of purifier–clarifier unit in the first place, it is possible to make bunkering possibilities very flexible.

Fuel-oil separators of some kind have to be fitted, and the additional cost of fitting the correct heavy-fuel-oil centrifugal separators, which will deal both with diesel oil and the high-viscosity heavy oil fuel oils, is negligible when compared with the advantages to be gained and the economy which can be made by having such flexible fuelling arrangements.

MR W. L. COATS (written discussion) : Referring to the summer tanks it is stated that, owing to their location, the outer surface of the inboard side and bottom of these tanks corroded at a greater rate than the remainder of the structure. I would be glad if the author would explain the reason for this.

On the subject of corrosion generally, presumably consideration has been given to some of the more recent methods, such as zinc spraying which proved so effective on the Menai bridge, which have been tried out in other spheres for preventing corrosion. It would be of interest to know if any investigations have been made as to the effectiveness of such methods in marine work, and with what results.

With regard to the difficulty of cooking meals on board while discharging cargoes, would it not be possible to use steam-heated cooking equipment supplied from a storage receiver charged from the ships' boilers before shutting down ?

The writer is particularly interested in the reference to the new type of heating coils which have been developed. Would the present state of development permit the author to state if equal advantages technically and economically would accrue from the fitting of such coils in shore tanks ?

Dealing with the steam gas ejectors, it is inferred that these are portable, and are attached as required to the ends of fixed evacuation pipes in the various tanks. It would appear that these ejectors might have a useful field in expediting the gas freeing of shore tanks, and in this connexion would it be possible to state

1. The cubic capacity of tank which can be effectively gas freed in 4 hr.
2. The minimum steam pressure required to operate the ejectors.
3. Could they be operated by compressed air, say, from a portable compressor, and if so what would be the minimum air pressure required, and the cubic feet of air per hour.

MR JOHN LAMB, in his written reply, said : The chairman's reference in his opening remarks to a 28,000-ton cargo being discharged in 20 hr is indicative of things to come and confirms the statement in my paper that

the turn-round of tankers in future must be greatly speeded up. I see no reason why tankers should not turn-round in 24 hr, which is about the time required for the Master to conduct his business and effect staff changes. This means that tankers must discharge their cargoes, no matter what the quantity may be, in about 16–18 hr to allow sufficient time for ballasting if the turn-round is to be accomplished in 24 hr. Such a short time in port may seem hard on the ships' personnel, but in view of the generous annual furlough granted to them, any complaints regarding quick turn-round would not be reasonable.

I am glad to have Mr Logan's contribution to the discussion, and as he rightly points out, the larger the tanker the lower will be the cost to transport a given quantity of cargo over a given distance, but before ships of the order of 30,000 tons can be generally employed not only must the berthing facilities be greatly improved throughout the world but also an adequate number of dry docks built to accommodate such large ships must be available.

As Captain Thomson will observe from reading my paper, I am of the same mind as himself regarding the usefulness of the 12,000-ton tankers for some time to come. It is true that I mention tankers in the order of 50,000 tons deadweight, but I would also point out that this was just a statement to the effect that such tankers can be built. Where such tankers could be used is an entirely different matter.

Captain Thomson is of the opinion that large tankers should be provided with twin screws. From the economic point of view, both in first cost and maintenance, duplicate machinery is undesirable, and most ship designers have endeavoured to get the desired manœuvring qualities with a single screw. That their endeavours have been highly successful is, I think, conclusively proved in the performance of ships up to 28,000 tons. As a matter of fact I know of many shipmasters who would prefer a single screw for any size of ship providing they get sufficient astern power out of that single propeller.

The heating of black-oil cargoes on board ship has been of a very haphazard character. Until quite recently ships' officers were under the impression that the higher the pressure of steam in the deck line the more heat was being transferred to the cargo. Actually, of course, the reverse is the case, since the longer the steam remains in the deck line the more condensation occurs, and hot water has no heating value. The present tendency is to reduce the steam pressure in the deck lines, and the best results are obtained when the pressure is sufficient only to expel the condensate from the heating coils. Such good results have been obtained regarding discharge rates from T.2 tankers that Captain Thompson can be forgiven for thinking that to obtain such results an electrically driven cargo-pump is necessary. The method of driving the pump has, of course, no effect upon the discharge rate. It is all a question of providing sufficient driving power. My own view is that the cargo-pump of the future will be driven by a steam turbine rather than by electric motors.

Mr Williamson raises some very interesting points in regard to the risks involved in having the cargo-pump driving unit in the engine-room. I would say that this matter is fully realized, and that it is possible to provide adequate safeguards against accidents such as he describes occurring. I

fully agree that when wing tanks are made unusually long, as they are in some tankers, duplicating the hatches would be a considerable advantage. The Shell do not favour these long wing tanks, but if and when we do adopt such a practice I shall have no hesitation in spending the little extra money on the provision of two hatches.

Regarding the diversity in the numbering of tanks, I agree with Mr Williamson that this must be very confusing to people not associated with the particular tanker. It has been the Shell practice since as far as memory goes to number the tanks from aft. Why they should have been numbered in this way I do not know, but it may interest Mr Williamson to know that we have for some time had under consideration the question of numbering the tanks from forward.

Mr Norling's remarks regarding the claims by various people to operate diesel engines on boiler fuels are timely, because of misleading statements made in conversation and in the Press. One manufacturer claims to have operated his engines on high-viscosity fuels twenty years ago, but apart from that no details are available. The facts are, however, that the use of high-viscosity fuel was soon discontinued, in spite of the substantial price differential between diesel fuel and boiler fuel.

I would here acknowledge the help which I have received from Mr Norling's company, who, when requested, immediately came forward with the very best machines they could produce, and after three years of experimenting I have no complaints whatsoever to make about their machines.

I am gratified to learn from Mr Skinner that the *Olna* designed by the Shell Marine Technical Division, has given absolutely trouble-free service. This performance agrees with the performances of the two similar ships still under the Shell House Flag.

I am glad that Mr Skinner agrees with my view that the port authorities should contribute their part to the reduction in the cost of ocean transportation of oil by deepening and improving port facilities generally to enable larger tankers to be employed.

In regard to the prevention of corrosion, I am of the opinion that metal spraying has distinct possibilities. The problem, however, is to find metal which will be suitable for the numerous grades of cargo carried by tankers, as it would appear that one metal will offer protection against a certain number of cargoes, but will completely break down when exposed to other grades.

I am interested to note that the Admiralty have developed a flexible hose which will withstand an internal pressure up to 200 p.s.i. This is a factor which, as mentioned in my paper, will have an important bearing upon the turn-round of tankers, and it is to be hoped that this latest development will be made increased use of by shore authorities.

Regarding Mr Skinner's enquiry upon the behaviour of the *Auris*, I would say that the machinery of this ship is so unusual that teething troubles were to be expected. These teething troubles, however, are being overcome, and at the present time it can be said that the whole installation is operating satisfactorily. For the benefit of other readers I would mention that the *Auris* is propelled by a diesel-electric installation comprising four high-speed diesel engines driving generators, the current generated being A.C.

In reply to Mr van Asperen, who enquires is there any reason for not

referring to the two-cycle engine in connexion with the burning of heavy fuel, I would say that two-cycle engines have not been specially mentioned in the various reports circulated by me, for the reason that Shell tankers are mostly propelled by four-cycle engines and that I have not yet attempted to burn high-viscosity fuels in two-cycle engines. I see no reason, however, why a two-cycle engine should not burn heavy fuel providing the compression is approximately the same as that in four-cycle engines and the fuel-pump located reasonably close to the fuel valves. This is necessary to avoid excessive radiation of heat from the fuel to the atmosphere, particularly when manœuvring in and out of port. My only experience of operating two-cycle engines was at Messrs Werkspoor's, when I witnessed the experimental two-cylinder engine operating most satisfactorily on fuel of 1500 sec Red. I at 100° F.

My reply to Mr Norling applies also to Mr Mackegg's useful contribution regarding the claims by various people to have operated diesel engines on boiler fuels. One of the criticisms made regarding the burning of heavy fuels in diesel engines is that the cleaning of the purifiers entails extra work for the engine-room staff; this in spite of my oft-repeated statement that the purifiers require to be cleaned only once a day. The purpose of these criticisms would seem to be to compel the makers of centrifugal separators to discover some method of cleaning the bowls without stopping the machine and opening up.

Regarding the various points raised by Mr Coates, in answer to the first I would say that it is presumed that the corrosion of the summer tanks was greater than any other part of the internal structure because of their location near the surface of the liquid, and in heavy weather they were alternately wet and dry for prolonged periods. The point regarding zinc spraying as a means of preventing corrosion is answered in my reply to Mr Skinner. Regarding the cooking of meals on board without naked lights, I would mentioned that most tankers are provided with steam cookers which are operated by steam from the shore. Such cookers, however, will not roast and there is a great reluctance amongst ships' personnel to live two or more days on food cooked by means of steam. Personally, I consider such reluctance unreasonable.

I know of no reason why cast-iron heating coils should not be used in shore tanks. Actually the problem in shore tanks is not so difficult as on board ships, since weight and flexibility are not important factors. The cubic capacity of a tank which can be effectively gas freed in four hours is given in the paper as 27,000 cu. ft. The time, of course, as mentioned depends upon the amount of scale adhering to the sides of the tank. The steam pressure usually employed for the gas ejectors referred to is 100 p.s.i. Regarding the enquiry in connexion with the operating of these gas ejectors by compressed air, I have to say that I have had no experience and should imagine that compressed air would be less efficient than steam.

In reply to Mr Pracy I would mention that the gas ejectors used are so effective that after the Explosimeter registers "zero" it is impossible to detect by sense of smell that the tank has contained volatile cargo. It is, of course, a regulation that when a man enters the tank the ejectors must be kept in operation, so that the contents of the tank are being constantly changed at the rate of seven times an hour.

Regarding the dangers of leaded spirit, after prolonged discussion with authorities closely associated with this form of spirit, it was decided that in the case of cargo tanks of tankers the risk of injury to personnel engaged in cleaning such tanks was negligible, and in such circumstances it was not proposed to recommend that extraordinary precautionary measures should be taken. This ruling applies solely to the ordinary cleaning of ships' tanks in preparation for a further cargo, and does not apply to the operation of scaling ships' cargo tanks or in cases where repairs have to be carried out, as such operations create dust, and it is then necessary to follow closely the precautionary measures recommended by The Associated Ethyl Co. Ltd.

It is gratifying, to judge from the large attendance at the reading of the paper, that so many are interested in tanker construction. It is to be regretted, however, that metallurgical chemists and oil technologists did not come forward to give us the benefit of their views regarding such matters as corrosion of ships' plating and the unusual diesel-engine cylinder-liner wear when burning heavy fuel oils, as it is only through close co-operation between the engineer and the chemist that such problems can be solved.

THE PROPERTIES OF HYDROCARBON GAS-TURBINE FUELS.*

By D. A. Howes and H. C. Rampton.

[Abstract.]

This paper summarizes the information available on the properties of hydrocarbons boiling within the range 65° to 300° C with particular reference to their use as constituents of fuels for gas turbines. It is pointed out that these various properties, determined by chemical composition and configuration, are closely inter-related and that they mostly lie between the extremes set by the paraffins and the aromatics respectively. This means that any gas-turbine fuel comprised entirely of hydrocarbons will have properties within this range.

Available information on the hydrocarbon compositions of petroleum, Fischer–Tropsch, hydrogenation, and shale-oil fractions is summarized, and attention is drawn to the present lack of knowledge concerning hydrocarbon compositions in fractions boiling above the motor-spirit range. This is due to the considerable difficulties encountered in analysis.

The available methods of analyses are briefly reviewed, and the possibilities of synthetic methods for producing gas-turbine fuels of different hydrocarbon compositions are summarized.

Introduction.

The advent and rapid development of the gas turbine for aircraft propulsion has focused attention on its fuel requirements, and considerable effort is now being directed towards ascertaining the various chemical and physical properties of fuels which have a bearing on turbine performance. In the case of the volatile hydrocarbon fuels used in spark-ignition internal-combustion engines, the so-called motor gasolines or petrols, the basic properties of fuels which affect engine performance have been well established, and the petroleum industry has made available, in considerable quantities, gasolines which meet all the requirements of such engines ranging from those used in commercial vehicles and private cars to the most powerful aero engines. In the case of the diesel engine also, the various chemical and physical properties of hydrocarbon fuels which have a bearing on engine performance have been determined, and fuels are now available meeting all the various diesel-engine requirements. In the case of the aero gas turbine, however, the position is not so satisfactory, and considerable research may be necessary to provide the same basic data. Although the gas turbine would appear to be basically less exacting in its fuel requirements than internal-combustion engines, and although it is most desirable that its future development should be in the direction of making it suitable for operation on the widest possible range of fuels, it is very likely that for some time to come the gas turbine will not be able to operate fully satisfactorily on a wide range of fuels, particularly when used in aircraft.

Of the various fuels which may be considered for use in gas turbines, and particularly in aero gas turbines, the hydrocarbon fuels are by far the most

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important, because they are the only fuels available in the quantities required and at a reasonable price level. For this reason, in this paper, other possible fuels such as alcohols, ethers, etc., either for use in the undiluted state or mixed with hydrocarbon fuels, are not considered.

Hydrocarbon fuels are mainly produced from petroleum, and petroleum will continue to be by far the most important source of hydrocarbon fuels for a long time to come, although minor quantities may continue to be produced in various parts of the world by synthetic processes using coal and coke as raw materials and also by the retorting of oil shale.

The future development of the aero gas turbine will therefore be largely dependent upon petroleum, and it follows that the properties of hydrocarbon fuels produced from petroleum or capable of being produced economically from petroleum by conversion processes, should be appreciated by those responsible for gas-turbine development. Progress in this development will be more rapid if adequate measures are taken to ensure that gas turbines operate satisfactorily on hydrocarbon fuels which are either available now or which could be made available without long delay.

Aero-gas-turbine-fuel Specification.

Very little information has yet been published on specifications for aero-gas-turbine fuels. In the case of the fuels used by Germany in the late war, recent official publications reveal that they were, in the main, of the kerosine–gas-oil type, and statements have been made in the popular Press that, in the speed record set up by the " Meteor," ordinary " paraffin oil," *i.e.*, kerosine, was used as fuel.

One specification has, however, been published, namely British Ministry of Supply Specification DERD 2482 dated April 1, 1947, which is reproduced below :—

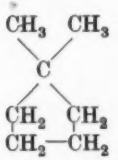
1.	Shall be wholly hydrocarbon.	
2.	Shall be clear and free from sediment, suspended dirt, and undissolved water.	
3.	Colour	4·0 Lovibond max.
4.	Water tolerance . . .	2·0 ml max.
5.	S.G. at 60° F . . .	0·810 max.
6.	Sulphur	0·10 per cent wt max.
7.	Copper strip corrosion . .	Slight discoloration max.
8.	Flash point . . .	100° F min.
9.	Viscosity at 0° F . .	6 cs max.
10.	Distillation . . .	20 per cent min to 200° C. F.B.P. 300° C max. Residue 2 per cent max. Loss 1·5 per cent max.
11.	Freezing point . . .	−40° F max.
12.	Aromatics	12 per cent max.
13.	Cal. val. (nett) . . .	18,500 B.Th.U./lb min.
14.	Existent gum . . .	6 mgm/100 ml max.

This specification is for a kerosine-type fuel, and it is likely that a petroleum middle distillate, probably of wider boiling range, will become accepted

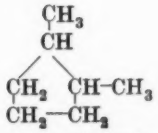
as the regular fuel. This will probably have a boiling range somewhere in the range 65° to 300° C, depending on turbine suitability, commercial availability, and price. In what follows, the boiling range 65° to 300° C has been assumed.

Hydrocarbons Present in Gas-turbine-fuel Fractions.

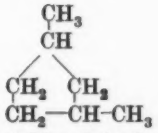
The information available concerning the composition, in terms of the individual hydrocarbons present, of petroleum fractions in this boiling range is most incomplete. The isolation of single hydrocarbons in a high state of purity followed by positive identification is extremely slow work, as instanced by the fact that researches carried out by the U.S. Bureau of Standards from 1927 onwards on the isolation of the hydrocarbons in a typical mid-continent petroleum and which so far has involved a total of about 200 man-years of effort, has resulted in the isolation and identification of only seventy-two different hydrocarbons; forty-six boiling below 150° C; thirteen between 150° and 200° C; and thirteen above 200° C.[1] So far this kind of information is only available concerning the lightest petroleum fractions in which the number of possible isomers of the various paraffins and naphthenes is not too great to allow reasonable separations to be made, but in the case of fractions boiling above 100° C the problem involved in effecting separation of individual hydrocarbons is very considerable. This is shown in Table I, which lists the number of possible paraffin hydrocarbon isomers in the aero-gas-turbine-fuel range 65° to 300° C. In the case of the naphthene hydrocarbons the possible number of isomers is even greater. So far the naphthenes isolated from petroleum belong to the *cyclo*pentane and *cyclo*hexane series in which, in addition to structural isomers, *cis–trans* isomerism is also found. This complicates the problem even further, and it is not surprising that up to the present only very few individual naphthene hydrocarbons have been isolated from petroleum. Thus in the case of the dimethyl *cyclo*pentanes alone five isomers are possible because both the 1 : 2- and 1 : 3-dimethyl*cyclo*pentanes can exist in both *cis* and *trans* forms.



1 : 1-Dimethyl*cyclo*-pentane.



1 : 2-Dimethyl*cyclo*-pentane *cis* and *trans*.



1 : 3-Dimethyl*cyclo*-pentane *cis* and *trans*.

Thus including methyl *cyclo*hexane and ethyl *cyclo*pentane there are seven isomeric naphthenes with a five- or six-membered ring containing seven carbon atoms. An increase to eight carbon atoms gives a possibility of eight possible trimethyl*cyclo*pentanes, five methyl ethyl *cyclo*pentanes, two propyl *cyclo*pentanes, seven dimethyl *cyclo*hexanes, and one ethyl *cyclo*hexane, making a total of twenty-three possible isomers.

In the case of the aromatic hydrocarbons the situation is much simpler. For example, in fractions boiling up to 200° C the aromatic hydrocarbons

contain only one ring per molecule. Thus neglecting stereo isomerism there are only twenty-two possible aromatic hydrocarbons containing ten carbon atoms compared with seventy-five paraffins with this number of carbon atoms. However, in fractions boiling above 200° C, complications arise due to the occurrence of bicyclic aromatics such as the alkyl naphthalenes, which have been isolated from a number of crude petroleums. In addition, partially or completely saturated bicyclic hydrocarbons are also known to occur, so that the number of possible isomers containing one or two rings boiling in the range 200° to 300° C is enormous.

TABLE I.

Possible Paraffin Hydrocarbons in Aero-gas-turbine Fuels, b.p. 65° to 300° C.

Number of carbon atoms.	General formula.	Number of possible structural isomers.	Boiling range of known isomers °C.	Number of isomers isolated from or identified in petroleum.	Number of isomers synthesized and properties determined.
6	C_6H_{14}	5	49·7– 68·8	5	5
7	C_7H_{16}	9	79·3– 98·4	6	9
8	C_8H_{18}	18	99·2–125·6	5	18
9	C_9H_{20}	35	122·3–150·7	6	31
10	$C_{10}H_{22}$	75	135·0–174·0	4	36
11	$C_{11}H_{24}$	159	160·8–195·8	—	17
12	$C_{12}H_{26}$	355	176·0–216·3	1	22
13	$C_{13}H_{28}$	802	206 –236·5	—	7
14	$C_{14}H_{30}$	1,858	215 –253·5	—	6
15	$C_{15}H_{32}$	4,347	240 –272·7	—	7
16	$C_{16}H_{34}$	10,359	268 –286·5	—	8

It will be appreciated therefore that several years at least must elapse before really detailed knowledge is available concerning the individual hydrocarbons present in gas-turbine fuels of boiling range 65° to 300° C produced from petroleum.

The position is very much the same in the case of fuels of this boiling range produced by the hydrogenation of coal which are also comprised of a very large number of hydrocarbons, most of which have not yet been identified. In the case of shale oil also the information is incomplete, and the problem is made more difficult in this case due to the presence of unsaturated, *i.e.*, olefinic, hydrocarbons. With regard, however, to Fischer-Tropsch product, because this normally contains only very small quantities of naphthene and aromatic hydrocarbons and because the paraffins and olefins present are largely straight-chain compounds the difficulty of separation is less pronounced, and more complete information is available.

Turning again to petroleum fuels, research on chemical composition by the isolation of individual hydrocarbons which has been in progress for several years and which is likely to continue for many more is supplemented by research on the synthesis of hydrocarbons of the many types present or likely to be present in petroleum distillates, in order to determine their chemical and physical properties. Owing to the very high standards of purity which have been set in this synthetic work, progress is

necessarily slow, but much valuable information is being accumulated, particularly in the gas-turbine-fuel range.

In addition to the work mentioned above, considerable effort has been directed to the development of methods of analysis by which the composition of petroleum distillates may be determined. Except in a few cases where these analytical procedures have been applied to individual hydrocarbons, they have mostly been used to determine classes or types of hydrocarbons. Thus paraffin hydrocarbons have been determined collectively, and methods have been worked out for the similar determination of naphthene, olefin, and aromatic hydrocarbons.

As in the case of the work on hydrocarbon isolation and synthesis, work on analytical methods has been largely restricted to the lower boiling hydrocarbons, and the position to date is that any distillate boiling up to about 150° C can now be analysed, with considerable precision, in terms of the following constituent hydrocarbon classes :—

Paraffins
Aromatics
Olefins —cyclic and acyclic
Naphthenes—*cyclo*pentane derivatives
*cyclo*hexane derivatives

In the case of fractions boiling up to about 220° C, methods are also available, although of somewhat reduced accuracy, but for higher boiling hydrocarbons the analytical methods available are not as yet very reliable and much more work remains to be done.

The methods of analysis employed are largely based on the determination of physical properties, such as density, refractive index, solution temperature in aniline (*i.e.*, aniline point), and selective adsorption on materials such as silica gel. Differentiation between certain *cyclo*pentane and *cyclo*hexane derivatives (C_5 and C_6 naphthenes) is effected by catalytic dehydrogenation followed by determination of the aromatics formed. Catalytic hydrogenation is employed to distinguish between cyclic and acyclic olefins.

As the boiling range increases, however, so do the difficulties of analysis. This is because, with rise in molecular weight, the different hydrocarbon classes become less distinct and merge into one another. For example, aromatic hydrocarbons with long paraffin side chains combine the properties of both aromatics and paraffins, and so become more difficult to classify. The polycyclic hydrocarbons also introduce complications, as also do hydrocarbons which comprise naphthenic rings and long paraffin side chains. Furthermore, *cyclo*hexane naphthenes with geminal carbon atoms do not dehydrogenate easily to the corresponding aromatics, and are for this reason not readily distinguished from the higher *cyclo*pentane naphthenes.

It will be evident from the foregoing remarks that our knowledge on the compositions of gas-turbine-fuel fractions from petroleum, or from other hydrocarbon sources, is far from complete, not only with regard to their constituent individual hydrocarbons but also with regard to the availability of analytical methods for determining the main classes of hydrocarbons present. Furthermore, despite the very considerable research effort being applied to these problems, it cannot be expected, during the

next few years, for the same detailed information to be available concerning the compositions of aero-gas-turbine fuels as already exists concerning normal aviation fuels. The problems involved are much more difficult than in the latter case.

The Properties of Hydrocarbons in the Aero-gas-turbine-fuel Range.

Despite the lack of knowledge concerning the chemical compositions of petroleum distillates in the higher boiling range of aero-gas-turbine fuels, some information is available on the physical properties of hydrocarbons which have a bearing on turbine behaviour, and this is summarized in graphical form in the accompanying figures. In a recent paper on aero-gas-turbine fuels C. G. Williams [2] has described the various fuel properties which are important in determining the suitability of various fuels for use in aero turbines and has listed them as follows : pumpability, ease of starting, combustion efficiency and stability, calorific value, dimensions of combustion zone, and nature of combustion products. It is, of course, true that the importance or otherwise of these various fuel factors is dependent on the detailed mechanical design of the turbine, the combustion chamber, and the various turbine auxiliaries, and it is hoped that future designs will be such as to minimize the effect of fuel variations and to make the aero gas turbine as omniverous as possible. On the other hand, the different classes of hydrocarbons present in turbine fuels do behave differently in pumpability at low temperatures, and in combustion characteristics, and it is with the object of drawing attention to these facts that the data contained in this paper are presented.

With regard to pumpability at low temperatures, and the behaviour of fuels in fuel tanks, fuel lines, and fuel pumps at low temperatures, the main factor involved is freezing point (*i.e.*, melting point), and if the fuel is to flow freely at low temperatures a low melting point is obviously necessary. A further factor involved is water solubility in the fuel over the operating temperature range and the extent to which dissolved water separates from the fuel at low temperatures.

Ease of starting necessitates a sufficiently low ignition temperature and an adequate range of inflammability when mixed with air. Similarly, the dimensions of the combustion zone are affected by the combustion characteristics of the fuel, and particularly by the ignition delay time over the temperature range involved. Ignition delay time is probably also a prime factor in determining the stability of combustion over a wide range of operating conditions.

The behaviour of hydrocarbons of different types boiling over the range 65° to 300° C in these and other respects are given in Fig. 1, density at 20° C; Fig. 2, Melting point; Fig. 3, Viscosity at 20° C; Fig. 4, Specific heat; Fig. 5, Latent heat of vaporization; Fig. 6, Heat of combustion; Fig. 7, Carbon content; Fig. 8, Spontaneous ignition temperatures; Fig. 9, Diesel index.

In these figures olefin and acetylene hydrocarbons have not been included because of the lack of detailed information concerning them and also because they do not occur in straight-run petroleum distillates.

Density (*Fig.* 1).

The various classes of hydrocarbon differ widely with respect to density. In the case of the paraffins, as the boiling point is increased from *ca* 80° C to about 300° C the density (at 20° C—grams/ml) increases from about 0·68 to 0·78–0·80. In the case of the naphthenes the range is from about

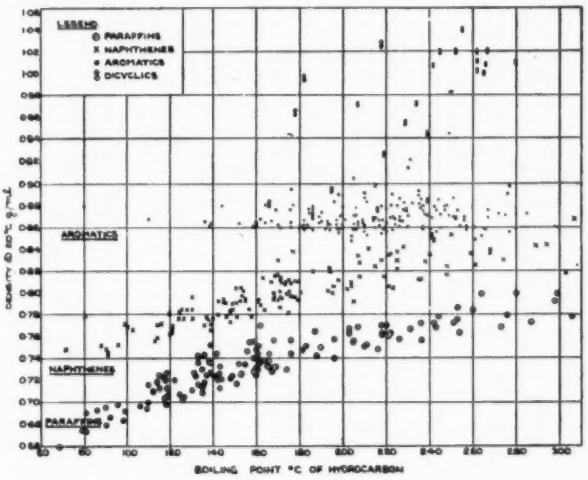


FIG. 1.
DENSITY–BOILING-POINT RELATIONSHIP OF HYDROCARBONS.

0·74 to 0·84, while in the case of the aromatics the band is much narrower and is from about 0·86 to 0·90. Dicyclic hydrocarbons vary from about 0·92 to 1·04, but as these do not constitute a major part of petroleum distillates it can be said that for all practical purposes the aromatics have the highest densities and paraffins the lowest.

Melting Point (*Fig.* 2).

Much more information is required on the melting points (freezing points) of hydrocarbons boiling above 100° to 150° C. In the case of the paraffins the normal isomers have, in general, the highest melting point, and as the amount of branching of the chain increases the melting point decreases. On the other hand, there is some evidence that the most compact molecular configurations, *i.e.*, the most highly branched, have melting points much higher than the normal isomers. There would thus appear to be an optimum amount of chain branching for minimum freezing point. Data available for the paraffin hydrocarbons are given in Table II.

In the case of the aromatic hydrocarbons the effect of side-chain substitution is somewhat similar. Thus benzene has a melting point of 5·5° C, toluene −95° C, 1 : 4-ditertiary butyl benzene +78° C, and pentamethyl benzene +54° C. The naphthene hydrocarbons, for which only meagre data are available, appear to behave in a comparable manner.

TABLE II.

Melting Points of Paraffin Hydrocarbons.

Number of carbon atoms.	Configuration.					
	Number of substituent groups or branchings.					Symmetrical highly branched structures.
	0	1	2	3	4	
6	−95·4					
7	−90·6	−118 to −119	−119 to −135	−25		
8	−56·9	−115 to −119	−90 to −138	−107 to −119		+101·6 (Hexamethylethane)
9	−53·7	−80 to −115	−41 to −117	−106 to −130	−9 to −120	
10	−29·7	−74 to −98	−53	−105		
11	−25·6	−93				
12	− 9·6	−70				
13	− 6·2	−65				
14	+ 5·5					
15	10·0					
16	18·1					+74·2 (2 : 2 : 3 : 3 : 6 : 6 : 7 : 7-Octamethyloctane)
17	21·0					

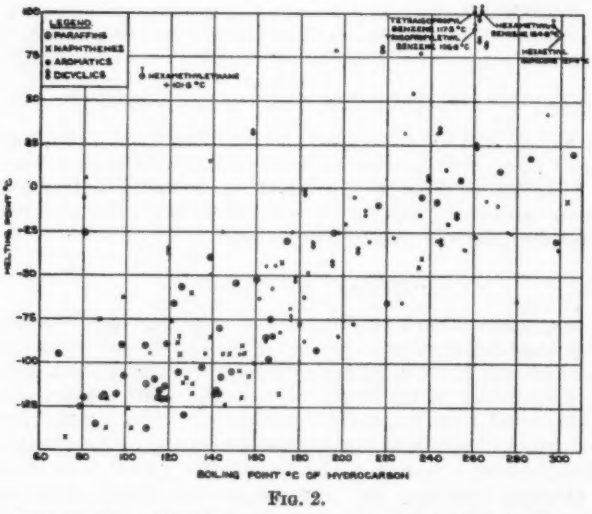


FIG. 2.

MELTING-POINT–BOILING-POINT RELATIONSHIP OF HYDROCARBONS.

For the present, however, the hydrocarbons mainly responsible for difficulties in meeting the low freezing points required in aero-gas-turbine fuels are the higher normal paraffins. It is shown in Table II that, in this series, melting point increases regularly with boiling point, and the straight-

chain pentadecanes and hexadecanes constitute the softer paraffin waxes. There is thus a relationship between distillation end point or final boiling point and the temperature at which these normal paraffin hydrocarbons separate in the solid form on cooling. In the case of petroleum containing appreciable quantities of these hydrocarbons it may therefore be necessary to restrict the upper limit of the boiling range in order to avoid this separation.

Viscosity at 20° C (Fig. 3).

Viscosity data for individual hydrocarbons, unfortunately, is sparse and prevents a full presentation of this property in relation to hydrocarbon

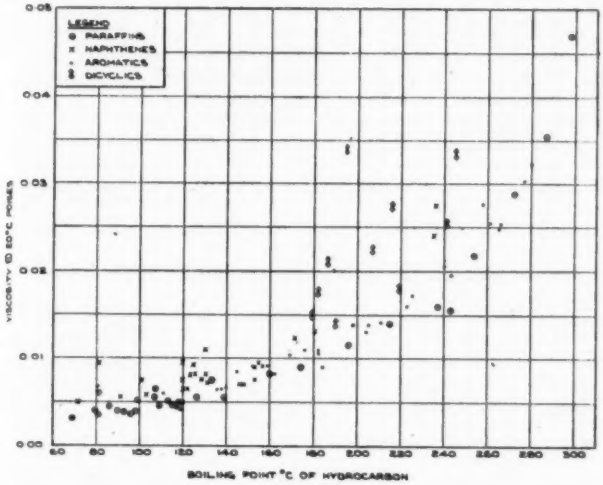


FIG. 3.

VISCOSITY–BOILING-POINT RELATIONSHIP OF HYDROCARBONS.

type. The main hydrocarbon classes have similar viscosities which increase steadily from a value of *ca* 0·003 poise to *ca* 0·050 poise throughout the boiling range 65° to 300° C. The rate of increase in viscosity is more pronounced above 240° C boiling point at which point the mean value is about 0·020. The dicyclic compounds tend to be rather more viscous than other hydrocarbons of the same boiling point.

Specific Heat (Fig. 4).

The data available suggests that the specific heats of all classes of hydrocarbon range between 0·40 and 0·53 at 20° C, the upper limit comprising that of the lighter paraffin hydrocarbons, and the lower that of the heavier aromatic hydrocarbons.

Latent Heat of Vaporization (Fig. 5).

A progressive decrease in latent heat of vaporization is observed with rise in boiling point of all groups of hydrocarbons, the paraffin value falling

from 80 to 40 g.cal and the aromatics at a slightly higher level from 95 down to 50 g.cal. The few available naphthene figures are intermediate between the paraffins and aromatics.

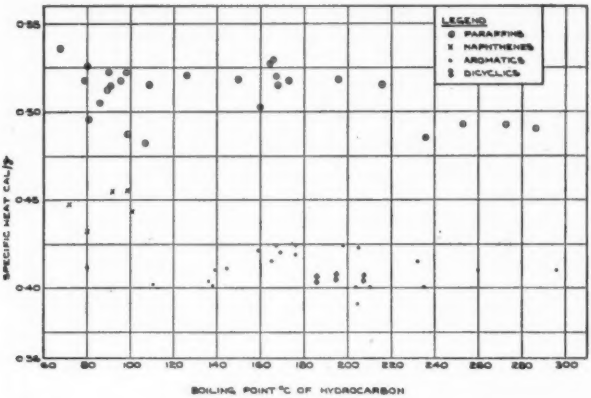


FIG. 4.

SPECIFIC HEAT–BOILING-POINT RELATIONSHIP OF HYDROCARBONS.

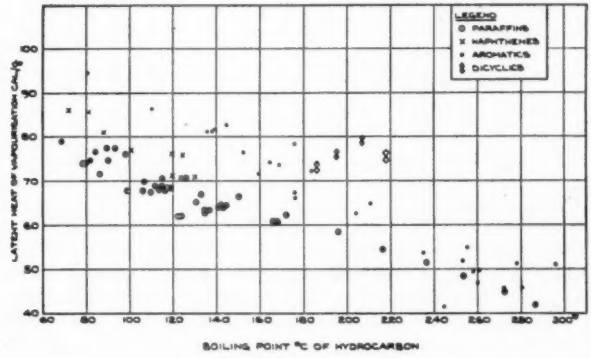


FIG. 5.

LATENT-HEAT-OF-VAPORIZATION–BOILING-POINT RELATIONSHIP OF HYDROCARBONS.

Heats of Combustion (*Fig.* 6).

Of the various classes of hydrocarbons the paraffins have the highest heats of combustion per unit weight. The naphthenes are intermediate between the paraffins and the aromatics, while the dicyclics have the lowest heats of combustion. In general, hydrocarbons of the highest hydrogen content have the highest heats of combustion. In any series, variation with boiling range is comparatively small.

Heat of combustion is an important characteristic of aero-gas-turbine

fuels, because to a large extent it determines fuel consumption and, as the overall efficiency of the gas turbine is not high, fuel consumption is correspondingly high and must be reduced as far as possible. The range of an aircraft propelled by a gas turbine clearly depends upon the total heat content of the fuel carried, *i.e.*, upon the product of heat of combustion per unit weight and total weight of fuel. On the other hand, in some cases there may be space limitations in an aircraft, and in this case it is necessary to fill the available fuel space with as many heat units as possible. In this case high heat of combustion per unit volume of fuel becomes important.

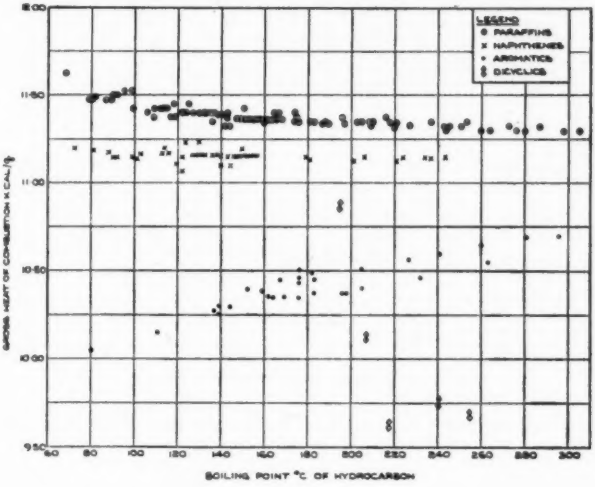


FIG. 6.

HEAT-OF-COMBUSTION–BOILING POINT RELATIONSHIP OF HYDROCARBONS.

The data for heats of combustion of hydrocarbons given in Fig. 6 are gross values expressed in kilogram calories per gram. To convert to B.Th.U./lb these values should be multiplied by 1800. The range of values for the paraffins is from 11·65 k.cal/g for normal hexane to 11·30 k.cal/g. for paraffins boiling at about 300° C. These values are equivalent to 20,970 and 20,340 B.Th.U./lb and 138,420 and 156,620 B.Th.U./gal respectively.

In the case of the naphthenes, the heats of combustion cover the narrow range 11·06 to about 11·23 k.cal/g, while those of the aromatics range from 10·04 to 10·70 k.cal/g. In the case of dicyclic hydrocarbons the value may be as low as 9·7 k.cal/g.

On a volume basis the aromatic hydrocarbons have heats of combustion ranging from 159,190 B.Th.U./gal to 172,220 B.Th.U./gal over the boiling range 80° to 300° C.

Carbon Content (*Fig.* 7).

The naphthene or polymethylene hydrocarbons have a constant carbon content or C–H ratio independent of boiling point. The carbon contents

of the paraffins are slightly less than those of the naphthenes and increase gradually through the boiling range from 83·7 per cent to 85 per cent. The aromatics show the greatest variation, the value falling gradually from 92·3 per cent for benzene (b.p. 80° C) to 87·7 per cent for hydrocarbons of boiling point 300° C.

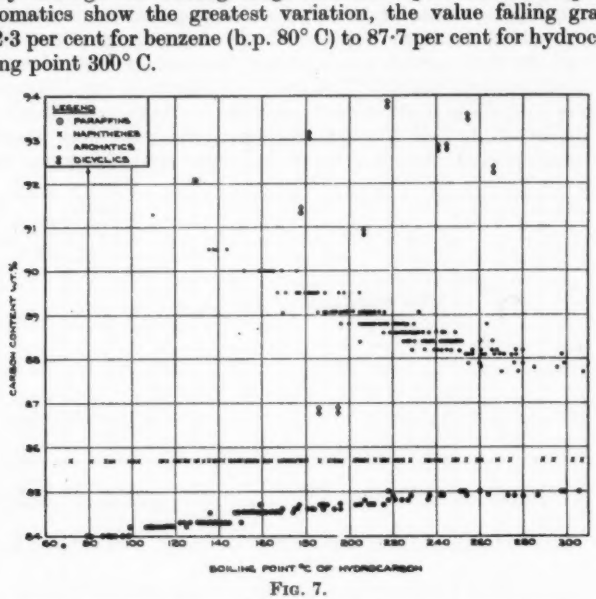


FIG. 7.

CARBON-CONTENT–BOILING-POINT RELATIONSHIP OF HYDROCARBONS.

SURFACE TENSIONS.

Insufficient data are available to allow graphical representation, but the available figures indicate that paraffins have the lowest surface tensions, from 18 to 28 dynes/cm at 20° C, naphthenes have slightly higher values ranging from 22 to 29 dynes/cm at 20° C, while the aromatics are highest at 28 to 32 dynes/cm at 20° C.

IGNITION AND COMBUSTION CHARACTERISTICS.

The desirable characteristics of a gas-turbine fuel from the point of view of ignition and combustion have not yet been adequately determined. Research is in progress on this subject, but it is as yet only possible to give a broad outline. It would appear that ignition lag, carbon formation, flame length, and range of allowable fuel–air mixture strengths are all important. Ease of atomization over the range of air temperatures and pressures existing in combustion chambers is also a contributing factor.

One important point in gas-turbine combustion is that the heat release per unit volume of combustion chamber is very high and that the permissible length of the combustion zone is strictly limited by design considerations. This means that the flame zone must be as close as possible to the fuel-injection nozzle, *i.e.*, the ignition-delay time must be short.

This means, in general, that the fuels giving the best performance in this respect will be those of low spontaneous ignition temperature and low ignition-delay characteristics, *i.e.*, the normal paraffins. The aromatic hydrocarbons have, in general, high ignition temperatures, and the naphthenes are intermediate between the aromatics and the paraffins. In other words, the best fuels from the ignition point of view will be of the same type as those giving the best ignition performance in the diesel engine, *i.e.*, fuels of high cetane number and high "paraffinicity."

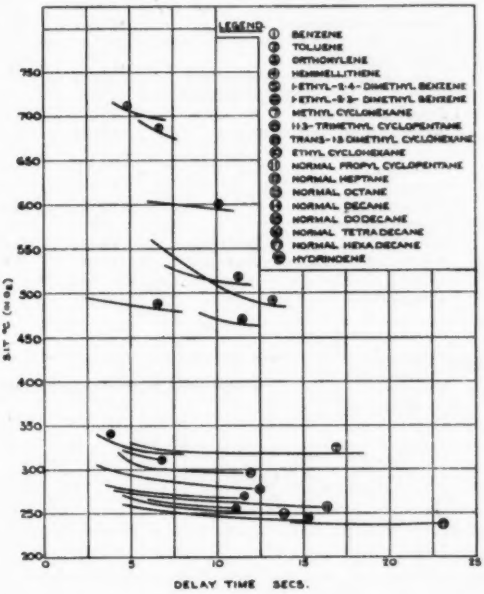


FIG. 8.

SPONTANEOUS-IGNITION TEMPERATURES OF HYDROCARBONS.

Very little information exists in the literature on the spontaneous ignition temperatures of pure hydrocarbons or on their delay–temperature characteristics, and Fig. 8 gives some values recently determined in the Research Department of the Anglo-Iranian Oil Company at Sunbury-on-Thames. These were measured in a stream of oxygen in a Jentzsch apparatus and are also listed in Table III. The results show that the paraffins have the lowest S.I.T.s, and aromatics the highest, the naphthenes being intermediate. The same relationship is shown concerning diesel index, values for which are plotted in Fig. 9.

With regard to carbon formation in the combustion chambers of aero gas turbines it is generally believed that the presence of aromatics in the fuel is an aggravating factor, although no conclusive evidence on this has yet been presented. Similarly, with regard to the possible harmful effects

TABLE III.

Spontaneous Ignition Temperatures in Oxygen of Pure Hydrocarbons.

Hydrocarbon type.	Member.	Boiling point, °C.	Delay time, sec.	Lowest S.I.T., °C.
Paraffin .	Normal heptane	98·4	16·0	256
	Normal octane	125·6	11·5	260
	Normal decane	174·0	13·5	250
	Normal dodecane	216·3	15·0	240
	Normal tetradecane	253·5	11·0	255
	Normal hexadecane	286·5	23·0	238
Naphthene .	Methyl*cyclo*hexane	100·9	18·5	312
	1 : 1 : 3-Trimethyl*cyclo*pentane	116·0	8·0	319
	trans-1 : 3-Dimethyl*cyclo*hexane	120·7	6·5	313
	Ethyl*cyclo*hexane	130·4	11·5	297
	Normal propyl*cyclo*pentane	130·8	12·0	278
Aromatics .	Benzene	80·1	7·0	697
	Toluene	110·7	8·0	670
	Orthoxylene	144·5	11·0	594
	Hemimellitene	176·1	14·0	486
	1-Ethyl-2 : 4-dimethylbenzene	184·0	12·0	510
	1-Ethyl-2 : 3-dimethylbenzene	186·0	12·5	463
Dicyclic .	Hydrindene	178·0	8·0	479

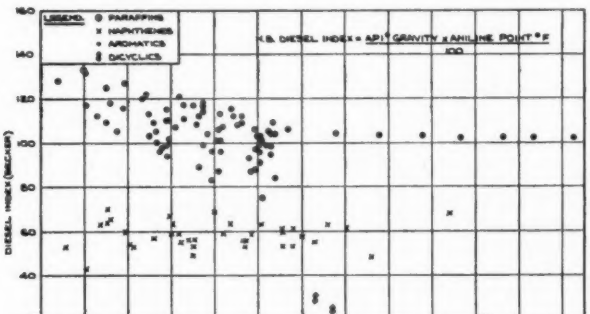

LEGEND. O PARAFFINS
X NAPHTHENES
• AROMATICS
‡ DICYCLICS
K.B. DIESEL INDEX = API GRAVITY x ANILINE POINT °F / 100
DIESEL INDEX (MACHAM)
• AROMATICS GENERAL LEVEL BELOW O
BOILING POINT °C OF HYDROCARBON

FIG. 9.

DIESEL INDEX–BOILING POINT RELATIONSHIP OF HYDROCARBONS.

of combustion products on turbine-blade materials, no evidence is yet forthcoming on the effect of fuel sulphur content.

THE AVAILABLE RANGE OF PROPERTIES IN HYDROCARBON AERO-GAS-TURBINE FUELS

It is evident from the data presented in Figs. 1 to 9 inclusive that the properties of hydrocarbons boiling in the range 65° to 300° C, which are

determined by chemical composition and structure, are closely interrelated and that, if the dicyclic and polycyclic hydrocarbons are ignored (this is justifiable because they are not major constituents of petroleum distillates), the properties lie between tolerably well-defined extremes set by the paraffins on the one hand and by the aromatics on the other. Thus any aero-gas-turbine fuel in this boiling range comprised entirely of hydrocarbons will have properties falling between these two extremes. These limits, for the hydrocarbons on which information are available, are given in Table IV.

TABLE IV.

Limits of Properties of Hydrocarbons, b.p. 65° to 300° C.

Property.	Lower limits.			Upper limits.		
	At 65° C.	At 300° C.	At mean B.P.	At 65° C.	At 300° C.	At mean B.P.
Density at 20° C g/ml .	0·66	0·77	0·74	0·88	0·89	0·88
Viscosity at 20° C poises .	0·003	0·04	0·010	0·010	0·06	0·015
Specific heat . . .	0·41	0·37	0·40	0·54	0·50	0·53
Latent heat of vaporization, g.cal. . .	75·0	40·0	60·0	100	52·0	75·0
Carbon content wt % .	83·7	85·0	84·5	92·3	88·1	89·5
Hydrogen content wt % .	7·7	11·9	10·5	16·3	15·0	15·5
Heat of combustion :						
K-cal/g . . .	10·05	10·75	10·3	11·65	11·3	11·4
B.Th.U./lb . . .	18,090	19,350	18,540	20,970	20,340	20,520
B.Th.U./I.G. . .	138,400	156,620	151,850	159,190	172,220	163,150
Surface tension, dynes/cm	18·0	28·0	23·0	28·0	32·0	30·0

Thus, for example, the paraffins are responsible for the lowest densities, viscosities, latent heats, carbon contents, and heats of combustion (per unit volume), while the aromatics are responsible for the higher values of these properties. The paraffin hydrocarbons of straight-chain structure have high freezing points and low spontaneous-ignition temperatures.

It follows, from the manner in which these various properties are interrelated, that while some combinations of properties are possible in the same fuel, others are not, and, although blending of fuels of substantially different compositions can be resorted to in order to produce mixtures of intermediate characteristics, it is not possible, on the basis of existing knowledge, to escape from the following generalizations concerning straight-run petroleum distillates :—

(*a*) The highest ignition quality in terms of the highest diesel index or of the lowest spontaneous-ignition temperature is not associated with either

(i) the highest possible density or specific gravity, or
(ii) the lowest possible freezing point.

(*b*) For the highest heat of combustion per unit volume aromatic hydrocarbons are necessary, whereas the paraffins are necessary in order to secure the highest heat of combustion per unit weight. Thus optimum ignition quality, while obtainable simultaneously with high

heat of combustion per pound weight, is not compatible with the highest heat of combustion per gallon volume.

(*c*) For the lowest possible freezing-point hydrocarbons of the most favourable ignition and combustion characteristics, *i.e.*, the normal paraffins, must give way to those of less favourable combustion properties, *i.e.*, the branched-chain paraffins, the substituted *cyclo*pentanes and *cyclo*hexanes, and the substituted monocyclic aromatics.

(*d*) The available ranges of viscosity, specific heat, latent heat of vaporization, carbon content, heat of combustion, and surface tension are relatively limited.

These conclusions may be modified somewhat as further information is made available concerning the properties of hydrocarbons boiling in the range 65° to 300° C, but it is believed that, in essence, they will remain.

The Possibilities of Producing Special Petroleum Fuels for Aero Gas Turbines by Synthesis or by New Conversion Processes.

If the various claims for the catholic taste of aero gas turbines for fuels are supported in actual experience, there should be no need to produce fuels by any means other than the simplest refinery processes, for example, distillation, etc. Indeed, it is hoped that the claims will, in fact, be fully substantiated so that fuels can be made available in the large volume required without unreasonable delay and at the requisite price level. The rapid development of the gas turbine for aviation will not be facilitated by imposing any restriction on fuel quality which is not proved to be essential, because this will reduce available fuel supplies.

It is unfortunately a fact that no synthetic process exists at the present time for producing fuels in the 65° to 300° C boiling range which in the light of present evidence would appear to be ideally suited to the aero gas turbine. To ensure the large supplies required, any such synthetic process must be based on petroleum, and the processes which have been developed for augmenting aviation-gasoline supplies, such as alkylation, polymerization, catalytic cracking, etc., are not suitable in their present state of development for producing turbine fuels. In the case of alkylation, products boiling above 200° C can be produced but not economically, and in the case of polymerization, which has so far been employed commercially to produce dimers and trimers, it is not yet known if good yields of the higher poylmers could be obtained. Catalytic cracking of heavier oils is a suitable method for producing products of the required boiling range, but these contain appreciable quantities of aromatic hydrocarbons. Furthermore, polymerization and catalytic-cracking processes produce products which contain appreciable quantities of olefins which so far have not been acceptable in aviation fuels. The same objection applies to the products of Fischer–Tropsch type processes, and it would appear that one of the first problems to be solved is how to use, in a fully satisfactory manner in aero gas turbines, fuels containing olefin hydrocarbons. These thermal-cracking processes could then possibly be used to produce the fuels required.

In conclusion, it is urged that aero-gas-turbine development should be along lines which will make this new and very promising prime mover as

independent as possible of fuel quality so that it can operate satisfactorily on the most abundant fuels available, namely regular petroleum distillates.

Acknowledgment.

The authors express their thanks to the Chairman of the Anglo-Iranian Oil Company for permission to publish this paper.

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THE BEAKER-CORROSION TEST FOR LUBRICATING OILS.

By F. W. H. Matthews.*

Summary.

This paper describes a laboratory test for evaluating the corrosive potentialities of lubricating oils towards cadmium–nickel bearing metal.

The object of its publication is to provide a "background picture" for the work at present in hand by I.P. Sub-Committee No. 6 on corrosion tests for automotive lubricants.

Experimental work is described, the object of which was to produce a test of suitable precision which at the same time would yield results correlating with those obtained by the Bristol single-cylinder Hercules engine test.

The test finally adopted yielded repeatable results showing reasonable correlation with engine tests. The apparatus and procedure adopted is described fully, explanatory diagrams and photographs being included.

Introduction.

With the increased speeds and bearing pressures resulting from modern engine developments came the necessity for the introduction on the working surfaces of bearings of suitable metals to withstand the new conditions.

Whilst such metals as silver–lead, lead–bronze, copper–lead, and cadmium–nickel were found to satisfy the engine demands on them, the problem of corrosion attained a new significance in engine maintenance, since certain of them, particularly the cadmium–nickel type, were found to be susceptible to corrosion by the lubricating oil used.

Engine tests were developed to ascertain the corrosive potentialities of lubricating oils, among which the Bristol single-cylinder Hercules test, in which cadmium–nickel bearings were used, became of primary interest during the war. Such tests were, however, both time-consuming and expensive.

The need for a laboratory test to replace engine tests was therefore necessary if only to serve as a sorting test to reduce the number of oils requiring examination in the engine, and during the war this need became acute.

In laboratory tests the chief factors leading to corrosiveness in lubricating oils appear to be: (1) temperature, (2) aeration leading to oxidation, and (3) the presence of metallic surfaces of different types acting as catalysts in accelerating deterioration.

Of the tests available in 1939 for laboratory evaluation of corrosion of bearings by lubricating oil, that due to Underwood was tried.† The apparatus gave valuable service, but suffered from certain disadvantages, viz., large size, large volume of sample required, difficulty of cleaning, and poor temperature control.

As a result of the experience gained with the Underwood test, the re-

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* Anglo-Iranian Oil Co. Ltd.

† Underwood, A. J. V. *J. Soc. Aut. Engrs*, 1938, **43**, 388.

quirements for a suitable laboratory test became clarified and a comparatively simple test was devised. This was designated the "Beaker-Corrosion Test," and during the war was used with success as a preliminary "sorting test" for aircraft lubricating oils and for assessing the response of such oils to inhibitor corrosion additions.

Preliminary Experiments.

The aim of the laboratory test was to produce, as simply as possible, a corrosive condition of the oil in the presence of another metal acting as a catalyst and thereafter to find the optimum conditions for obtaining correlation with the results of the Bristol single-cylinder Hercules engine test.

The test devised consisted in rotating in the oil at 160° C under controlled aeration conditions a specimen of bearing metal, the corrosion of which was measured in terms of periodic losses in weight.

Cadmium–nickel bearings were chosen as the reference bearing specimens, and a copper strip was employed as a catalyst. The oil temperature of 160° C was chosen as a result of experience with the Underwood apparatus and with automobile engines.

Aeration was accomplished by making use of the bearing design. The cylindrical Bristol cadmium–nickel floating bushes, of 3-in O.D., were parted off into $\frac{1}{2}$-in rings on a lathe, and the rings were sawn into quadrants. Each quadrant was drilled centrally and tapped and screwed, concave side downwards, on the lower threaded end of a steel shaft. This was positioned in the oil contained in a beaker, so that the upper convex face was just below the surface of the oil when at rest. When this stirrer was rotated, violent agitation took place resulting in considerable aeration and splashing.

The beakers used were 1500 ml, Pyrex, tall-form type and were covered by clock glasses drilled to accommodate both the stirrer shaft and thermometer. The copper catalyst was bent into a similar shape to that of the bearing specimen, and was made of $\frac{1}{32}$-in-thick sheet copper measuring 3 by $1\frac{1}{4}$ in. This was placed, concave side downwards, on the bottom of the beaker which contained a 2-in depth of oil. Both bearing specimen and catalyst were polished with fine emery paper before use and washed free from oil and grease with petroleum spirit.

In the first tests carried out using this apparatus, the weighed bearing specimen was removed from the oil at convenient intervals, washed free from oil with petroleum spirit and re-weighed. The process of stirring and weighing was continued until the specimen showed a weight loss of 500 mg or more. The losses in weight were then plotted against time, and the times required to produce losses of 10, 100, and 500 mg were deduced from the graph.

In Table I results obtained on four typical aero-lubricating oils are given, and the plot of these results is shown in Fig. 1. The times required to produce weight losses of 10, 100, and 500 mg as deduced from Fig. 1 are given in Table II.

The curves obtained show that there is an initial "induction period" for each oil during which little corrosion takes place, and after this period corrosion continues at a uniform rate, since the upper portion is linear. This proved to be a common feature of all tests carried out irrespective of

TABLE I.

Beaker-Corrosion Test: Results of Duplicate Tests on Four Aero-Lubricating Oils of Known Corrosive Properties as Determined by Engine Tests.

Catalyst: Copper, 3 × 1½ in.
Temperature: 160° C.

Hours run.	Loss in weight of bearing specimen, mg.							
	Oil A.		Oil B.		Oil C.		Oil D.	
7½	127	163	1	0	0	0	0	0
10½	263	312	1	0	45	89	0	0
13½	420	478	7	4	183	199	0	0
16½	582	667	95	28	371	318	2	1
20½	770	865	245	145	578	459	10	1
24½	—	—	428	297	791	648	54	11
28	—	—	573	487	—	—	177	36
31	—	—	762	636	—	—	325	80
33½	—	—	855	815	—	—	403	149
37½	—	—	—	906	—	—	545	297
45½	—	—	—	—	—	—	880	640

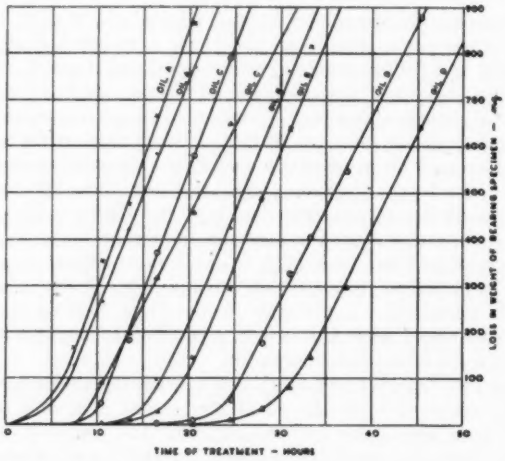

FIG. 1.

LOSSES IN WEIGHT OF CADMIUM–NICKEL BEARING SPECIMENS ON ROTATING IN OIL AT 160° C IN THE PRESENCE OF COPPER CATALYST (DUPLICATE TESTS).

modifications introduced subsequently. The results showed that the four oils could be placed in the ascending order of merit A, C, B, D, A being classed as corrosive and D as probably non-corrosive.

By the Bristol single-cylinder Hercules test oils were rated as "pass" or "fail" according to whether corrosion of the cadmium–nickel big-end bearing took place or not as evidenced by engine behaviour and inspection and weight loss of the bearing at the conclusion of the test. Two tests were

TABLE II.

Beaker-Corrosion Test: Results of Duplicate Tests on Oils, A, B, C, and D. Times Required to Produce Losses of 10, 100, and 500 mg.

Oil.	Hours required to obtain weight loss of		
	10 mg.	100 mg.	500 mg.
A	2 2	6¼ 7	13½ 15
B	13 14	17 19½	25½ 28¼
C	8½ 8	11½ 11	19 21¼
D	20½ 24½	25½ 31½	35½ 41¾

available, designated respectively Type II and Type III. In each case the engine was operated at a speed of 2400 r.p.m. at 77 b.h.p. and was run for 30 hr duration or until bearing failure was evident. In the case of Type II test, the oil-feed temperature was 90° C, but for the Type III test this was raised to 120° C, resulting in the more severe operating conditions.

The four oils were rated by this test as follows :—

Oil A—Failed Type II test
Oil B—Passed Type II test
Oil C—Failed Type III test
Oil D—Passed Type III test.

It is thus seen that of these oils, A is rated in the engine as corrosive and D as non-corrosive, which is the same order of merit as that obtained by the laboratory test.

B is intermediate between A and D, but the relative merits of B and C by the engine test, however, are in doubt.

TEST DEVELOPMENT.

Although this preliminary work was promising, it was agreed that greater precision was desirable in order to yield adequate differentiation between oils of different corrosive potentialities and ultimately to obtain good correlation with engine-test results.

To obtain this improved precision, experimental work was carried out to find the effects of the following factors which experience had shown to require investigation :—

(*a*) "lacquering," or the otherwise rendering insensitive of the metal surfaces of bearing specimen and catalyst;
(*b*) ventilation of the beaker during the test;
(*c*) optimum area of catalyst to be employed;
(*d*) optimum temperature for the oil during test.

This work forms the subject of the following sections :—

A.—*Lacquering of the Bearing Specimen and Catalyst Surfaces.*

Two considerations led to the investigations regarding lacquering of the metal surfaces in the test. First, it was observed on examination of the bearing specimens and catalysts during testing that certain oils, particularly those containing anti-corrosion additives, possessed the property of forming a varnish or lacquer on the metal surfaces. It was considered that this rendered the surfaces insensitive to corrosion and not only unduly prolonged the test but also gave misleading indications of the corrosive potentialities of the oils. The second consideration was the desirability of simulating conditions obtaining in the engine, and in this connexion it is possible that lubricating oil is in contact at regular intervals with metallic surfaces which, due to either rubbing action or to the effect of volatile acids derived from the oil, are continually being renewed.

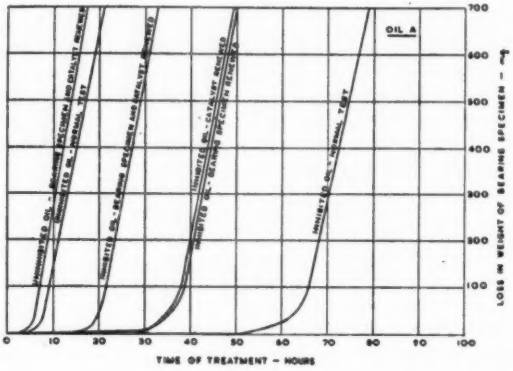

FIG. 2.

EFFECT OF RENEWAL OF CATALYSTS AND BEARING SPECIMENS AND EFFECT OF ADDITION OF ANTI-CORROSION INHIBITOR.

It was decided, therefore, to carry out tests by presenting freshly polished metal surfaces to the action of the oil at definite intervals. Using a fresh supply of Oil A, this was done by changing the bearing specimens and copper catalysts and replacing them by freshly polished ones.

In the first instance, the copper catalyst only was renewed at intervals of 2 hr. In a second test, the bearing specimen only was renewed at intervals of 4 hr and finally both catalyst and bearing were renewed, the former at 2-hr intervals, and the latter at 4-hr intervals. Since fresh bearings were used in these tests, the total losses in weight were obtained from the sum of the individual losses of each of the fresh specimens used. It was also found convenient to remove and weigh the bearing specimen at intervals of 2 hr instead of at irregular intervals as was carried out in the original test outlined.

Typical results of such tests on Oil A with and without the addition of anti-corrosion inhibitor are shown in Fig. 2. From these results it may be

inferred that with oils showing corrosive properties the effect of the renewal of the metal surfaces was not very marked. Oils, however, whether inhibited or not, showing mildly or non-corrosive properties, responded markedly to the modification. Thus the non-corrosion of bearing surfaces by certain oils and the action of the inhibitor may be due, at least in part, to the formation of a protective coating on the surface of the metal.

If the linear portions of the curves are produced downwards to cut the time axis a useful measure of the " induction period " before the onset of corrosion is obtained from the time indicated at the point of intersection. It would also seem that this figure could be used as an index for engine-test correlation. The time thus deduced was designated the " Breakdown Time."

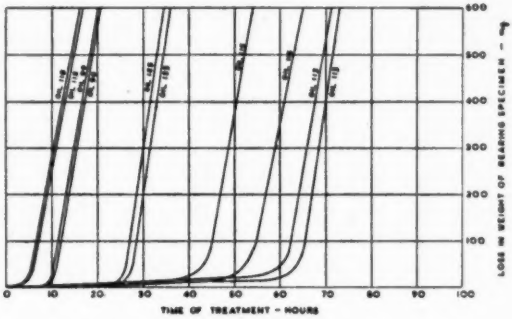

FIG. 3.

REPEATABILITY OF RESULTS WHEN USING BEARING SPECIMEN AND CATALYST RENEWAL MODIFICATION.

Thus the Breakdown Times of the oils shown in Fig. 2 are :—

	Breakdown, time, hr.
Uninhibited oil (original test)	7
,, ,, (bearing and catalyst renewed) .	5¼
Inhibited oil (original test)	64
,, ,, (catalyst renewed)	36
,, ,, (bearing renewed)	36¾
,, ,, (bearing and catalyst renewed) . .	19¾

It was concluded from these experiments that lacquering of the bearing specimen and catalyst was likely to occur and it was considered that the effect had been minimized by the renewal procedure described.

In order to try out this modification in procedure from the point of view of repeatability and correlation with engine-test results, experiments were carried out in duplicate on five oils for which the engine-test behaviour was known. In Fig. 3 a plot of the results is given from which the data shown in Table III have been deduced.

Except for sample 115, the repeatability of results is seen to be satisfactory—that is, duplicate results are close enough to preclude any confusion between different oils.

As regards correlation with the engine-test results, the breakdown times, with the exception of sample 125, are in the same relative order as the "pass" or "fail" results.

TABLE III.

Beaker-Corrosion Test: Results of Tests Carried Out to Assess the Repeatability and Correlation with Engine Tests Using the Renewal of Bearing Specimen and Catalyst Procedure.

Temperature: 160° C.
Catalyst: Copper strip.

Oil sample no.	Test 1.				Test 2.				Engine test.	
	Hours required to obtain losses of			Breakdown time.	Hours required to obtain losses of			Breakdown time.	Results.	Bearing weight loss, g.
	10 mg.	100 mg.	500 mg.		10 mg.	100 mg.	500 mg.			
118	3¾	6¼	14¼	4¾	4	7	15	5	Failed type II	22
90	9	11¼	18¼	9¼	10	12	19	10	Failed type II	20
125	24¾	27	33	25¼	25¼	28¼	34¼	27	Failed type II	30
115	30	45	52¼	43¼	36	54¼	63	53	Passed type II	—
113	27	62¼	69¼	60¼	21	65¼	71¼	64	Passed type III	—

On the basis of these results, a tentative correlation formula was deduced as follows:—

(1) Oils having breakdown times of 10 hr or less failed to pass the engine test—Oils 118 and 90.

(2) Oils having breakdown times of 40 hr or more passed the engine test—Oils 115 and 113.

(3) With oils having breakdown times between 10 and 40 hr, the results remain in doubt—Oil 125.

The modification comprising the renewal of the bearing specimens and catalysts at regular intervals was adopted and used in all subsequent work.

B.—*Ventilation of the Beaker During the Test.*

For the purpose of studying the effect of aeration of the sample on the extent of corrosion of the bearing specimen, experimental beaker covers were designed which consisted of tin-plate lids, each fitted with a pair of sliding doors covering an aperture through which the bearing specimen could pass. The doors were arranged on opposite sides of the stirrer shaft, so that when pushed together, the beaker was effectively sealed.

The doors could be opened to remove the bearing specimen and thereafter rapidly closed, thus preventing undue loss of vapours during manipulation. Auxiliary doors were designed so that when pushed together circular apertures of various diameters were provided at the centre of the covers round the stirrer shaft. The top edges of the beakers were ground flat so that the metal covers could be fitted to them, allowing no gaps to be present between the surface of the lower clamping ring and the cover.

Using this apparatus, Oil C was tested, and the following results were obtained :—

Aperture completely closed—			breakdown time	24 hr.
,,	0·175 sq. in.	—	,,	$34\frac{1}{2}$,,
,,	0·20 ,,	—	,,	$41\frac{1}{2}$,,
,,	0·44 ,,	—	,,	54 ,,
,,	0·93 ,,	—	,,	above 70 hr.

It is evident then that the breakdown time of an oil depends upon the amount of breathing taking place, from which it may be deduced that the acidic vapours formed during the test contribute in no small degree to the corrosion of the bearing specimen.

C.—*Area of Catalyst.*

The foregoing experiments described, using tin-plate beaker closures, necessitated, owing to the design of the cover, a reduction in the area of

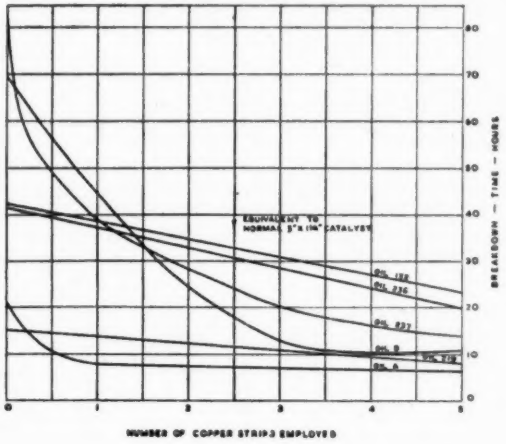

FIG. 4.

RELATION BETWEEN CATALYST AREA AND BREAKDOWN TIME FOR VARIOUS OILS.

copper catalyst employed. Some doubt existed as to the advisability of this reduction in catalyst area, and efforts were made to introduce more catalyst surface into the beakers with the metal covers. It was also the aim to find, if possible, the optimum area of catalyst consistent with adequate differentiation between various oils.

To this end small copper strips, bent into the same shape as the bearing specimen, were attached to the stirring shaft underneath the bearing specimen by means of a small steel adaptor.

The catalyst therefore rotated with the bearing specimen. Each of the strips was equal to approximately one-third of the area of the " standard " copper strip normally used. Up to five of these strips could be attached to the stirrer and introduced through the bearing aperture in the metal cover.

In Table IV the results obtained on six oils are given, together with the results obtained by the normal method and the engine-test results. In Fig. 4 a plot of the breakdown times against the number of small copper strips employed is shown.

Considering first the reaction to changes in catalyst area, it is observed that the response is roughly linear in four of the oils, whilst the remaining two show definite curves. From Fig. 4 it is obvious that if less than two copper strips were used, not only would the duration of the test be unduly prolonged for practical use, but also adequate differentiation between oils would not be obtained. It is also observed that the relative order of merit of the oils fluctuates in this region.

Secondly, having regard to the engine-test results given in Table IV, the best differentiation between the oils is found using two or two and a half small catalyst strips. The latter is almost exactly equal to the area of the catalyst originally employed ($7\frac{1}{2}$ sq. in.).

This was considered sufficient evidence to show that the size of catalyst originally employed was suitable for general use.

This form of catalyst was finally adopted when using metal beaker closures.

TABLE IV.

Beaker-Corrosion Test Results Using Small Copper Catalysts, Each Approximately One-Third the Surface Area of the Normal 3 × 1¼-in Catalyst and Rotating with the Bearing Specimen.

Beaker covers: Metal.
Temperature: 160° C.

Oil No.	Breakdown times in hours. No. of small catalysts employed. 0.	1.	2.	3.	4.	5.	Normal method (3 × 1¼-in catalyst).	Engine-test result.
132	42	33½	36½	30½	24½	26	46½	Passed type III
236	41½	36½	35	24½	27	32½	41½	Passed type II
237	>70	38¼	29½	22	22¾	13½	40¼	Passed type II
D	60	53	26	17	15½	16	23½	Passed type III
219	13½	14½	13	11½	8¾	8	12¼	Failed type II
A	22	8	9¾	7	5½	7	5½	Failed type II

D.—*Optimum Temperature for the Test.*

In all the tests so far described, the oil was maintained at a temperature of 160° C, and from the data already obtained for the Beaker-Corrosion Test, this temperature appeared to be suitable for the purposes required. It was unknown, however, whether this was, in fact, the optimum temperature consistent with adequate differentiation between different oils and good engine-test correlation.

To obtain information as to the effect of temperature on the test, oil D was selected and tests carried out at temperatures between 140° and 180° C in 10° increments. It was considered that sufficient information would be given by tests on one oil, since the previous experimental work had shown that variations in test procedure produced similar effects with most oils.

The results of these tests are shown graphically in Figs. 5 and 6. As

would be expected, an increase in temperature causes an earlier development of corrosion which continues thereafter at a practically constant rate. At 140° C there was no appreciable corrosion evident after 70-hr test duration; this ruled out any consideration of this temperature for test purposes.

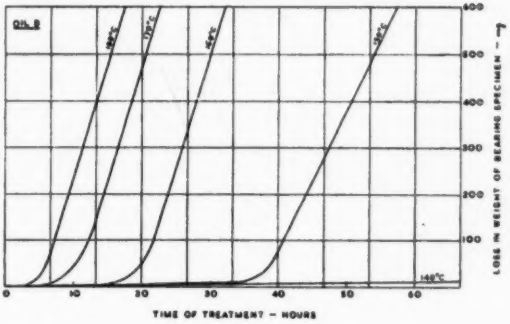

FIG. 5.

EFFECT OF CHANGE OF OPERATING TEMPERATURE.

Fig. 6 shows the log breakdown time–temperature relationship which is seen to be linear.

It was concluded that 180° C was too high and 140° C too low a temperature for successful operation of the test, and below 150° C the test would be too prolonged for practical use. The temperature of 160° C therefore appeared to be well suited to the test requirements.

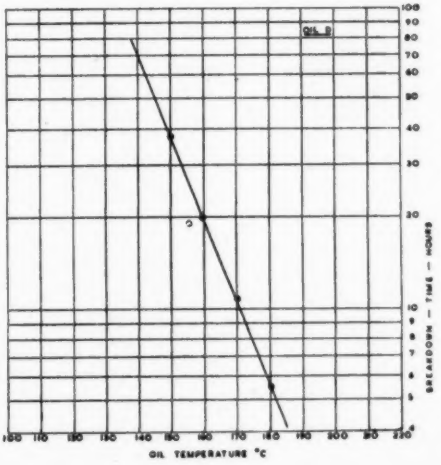

FIG. 6.

RELATION BETWEEN OIL TEMPERATURE AND BREAKDOWN TIME.

Precision.

A.—*Repeatability.*

Having decided on the test conditions, the results for a number of oils, selected as representative from about sixty oils tested, were collected and

Table V.

Results of Duplicate Beaker-Corrosion Tests on Various Lubricating Oils.

Oil No.	Inhibitor (tributyl-phosphite), %.	Breakdown time, hr.	Hours required to obtain bearing weight loss of			Mean breakdown time, hr.	Deviation from mean, hr.	Deviation from mean, %.
			10 mg.	100 mg.	500 mg.			
125	0·33	25½	24½	27	33	26¼	¾	2·9
		27	25½	28½	34½			
112	0·33	53¾	47	55	60¾	46½	7½	16·1
		39	34½	40½	45½			
90	—	9½	9	11½	18½	9¾	¼	2·6
		10	10	12	19			
113	—	60½	27	62½	69½	62¼	1¾	2·8
		64	21	65½	71½			
115	—	43½	30	45	52½	48	5	10·4
		53	36	53¾	63			
118	—	4¾	3¾	6½	14½	5	0	0
		5	4	7	15			
215	—	4¾	4	7	16½	4¾	0	0
		4¾	4	7	16½			
215	0·33	21	19¾	23	32	22½	1½	6·7
		24	23	26	34½			
216	—	5	4	7	15	7	2	28·6
		8½	5	10½	18			
216	0·33	14½	13	16½	22½	15½	1	6·5
		16¾	14¾	18½	25½			
205	—	10	8½	11½	18½	11½	1½	13·4
		13½	11	15	21½			
205	0·5	33½	20	35½	42½	35	1½	4·3
		36½	30½	38½	45½			
207	—	5½	4½	7	13	4½	¾	16·7
		4	3	6	14½			
207	0·5	>70	>70	>70	>70	>70	0	0
		>70	>70	>70	>70			
182	—	7	5½	8½	15	7¾	¾	9·7
		8½	8½	10¾	16½			
182	0·5	14½	9½	16½	23½	16½	2	12·1
		18½	10¾	19½	26			
183	0·5	22½	19	23¾	30	23½	1	4·3
		24½	23	26	32½			
132	—	43½	36½	45¾	56½	46½	2¾	6·0
		49	39½	51	60½			
218	—	9	8½	10½	17½	9	0	0
		9	8¾	11	18			
219	—	10¾	9	12½	18½	12½	2	16·0
		14½	11½	16½	23½			
228	0·5	21	8½	22½	29	21¼	¼	1·2
		21½	8½	23	29½			
236	0·5	38	35	39¾	46½	41¼	3¼	7·9
		44½	38	46½	53			
214	—	12½	11½	14	20½	12½	¼	2·0
		12¾	12½	14½	21½			
239	—	9½	7½	11	18½	9¼	0	0
		9½	7½	11¼	19			

are given in Table V. These are the results of duplicate tests carried out using a four-beaker heating unit.

From these figures it is found that the deviation from the mean breakdown time is small and possesses no significance when interpreting the test results.

The tendency, as may be expected, is for the non-corrosive oils of long breakdown times to exhibit a larger spread between duplicate tests than those of corrosive oils with short breakdown times.

The maximum deviation from the mean, as given in Table V, is 7½ hr, which is for a long-breakdown-time oil. Of the twenty-four oils listed sixteen show deviations of this amount or less.

This order of repeatability was found to be adequate for the requirements of the test.

B.—*Reproducibility.*

To obtain some idea as to the reproducibility of results, a few tests were carried out by different operators, on oils previously tested, in a second apparatus. These results and comparison with the previous tests are shown in Table VI.

TABLE VI.

Results of Beaker-Corrosion Tests on the Same Oils but in Different Apparatus.

Oil.	Breakdown time in hours.			
	Apparatus 1.		Apparatus 2.	
A + 0·1% T.B.P. . . .	19	21¼	21	21¼
A + 0·33% T.B.P. . . .	37½	38	40¼	41½
D	21¼	21¾	18¾	19¾

While these few tests do not provide sufficient data to calculate the reproducibility, they show that no marked difference is to be expected by using different operators and apparatus. The differences obtained are no greater than those for duplicate tests in the same apparatus.

CORRELATION WITH ENGINE-TEST RESULTS.

The results of tests carried out on thirty-nine oils form a suitable basis for final correlation, and these together with engine-test data are set out in Table VII, together with predicted engine-test results based on the following formula :—

(*a*) Oils having breakdown times of 10 hr or less are regarded as failing Type II engine test;

(*b*) Oils having breakdown times of 20 hr or less are regarded as failing Type III engine test;

(*c*) Oils having breakdown times of 10 hr or over are regarded as passing Type II and those of 20 hr or over as passing both Types II and III engine tests.

Analysis of these results shows, by comparison of the actual result of each engine test with the predicted result, that of the forty-two engine tests,

TABLE VII.

Correlation of Beaker-Corrosion Test with Engine-Test Results.

Oil No.	Whether containing additive (anti-corrosion).	Break-down time, hr.	Engine test results *			Predicted engine test result
			Type II.	Type III.	Bearing wt loss, g.	
50	No	16	Pass	Fail	18 (17 hr)	Pass II, fail III
85	No	5¾	Pass	Fail	21 (23 hr)	Fail, II and III
86	Yes	10¼	—	Fail	12 (26 hr)	Pass II, fail III
90	No	9½	Fail	—	20	Fail II
112	Yes	46	Pass	—	—	Pass II and III
113	Yes	62	—	Pass	—	Pass II and III
115	Yes	43¼	Pass	—	—	Pass II and III
118	Yes	5	Fail	—	22 (15 hr)	Fail II
106	Yes	26	—	Pass	—	Pass II and III
D	No	20⅝	—	Pass	—	Pass II and III
132	Yes	46¼	—	Pass	—	Pass II and III
135	No	5½	Fail	—	2·3	Fail II
A	No	6½	Fail	—	—	Fail II
205	Yes	35	Pass	—	—	Pass II and III
207	Yes	>70	Pass	—	1·5	Pass II and III
182	Yes	16½	Pass	—	1·7	Pass II, fail III
183	Yes	23½	Pass	—	3·6	Pass II and III
125	Yes	26	Fail	—	30 (21 hr)	Pass II and III
200	No	7¾	—	Fail	25 (10·5 hr)	Fail II
214	No	12½	Pass	Fail	21 (14 hr)	Pass II, fail III
218	No	9	Fail	—	23	Fail II
219	No	12¼	Fail	—	6	Pass II, fail III
228	Yes	21¼	Pass	—	—	Pass II and III
234	Yes	>50	Pass	—	—	Pass II and III
236	Yes	41¼	Pass	—	—	Pass II and III
237	Yes	40¼	Pass	—	—	Pass II and III
239	Yes	34½	Pass	—	—	Pass II and III
254	Yes	23	Pass	—	—	Pass II and III
262	No	30¾	Pass	Fail	22	Pass II and III
4	No	5½	Pass	—	—	Fail II
54	No	5½	Fail	—	(7 repeat 10)	Fail II
387	No	4½	Fail	—	11	Fail II
281	No	6¼	Pass	—	—	Fail II
281A	Yes	18	Pass	—	—	Pass II, fail III
281B	Yes	27⅛	Pass	—	—	Pass II and III
283	No	14½	Pass	—	—	Pass II, fail III
283A	Yes	26¾	Pass	—	—	Pass II and III
308	No	19	Pass	—	—	Pass II, fail III
308A	Yes	29¼	Pass	—	—	Pass II and III

* For conditions of test, see page 438, paragraph 2.

complete correlation was obtained in thirty-six cases. This is equivalent to 85·7 per cent correlation.

Oils failing to correlate were Nos. 85, 125, 4, 219, 281, whilst oil No. 262 shows correlation with the Type II engine test but fails to correlate with the Type III test. In this connexion it must be borne in mind that the comparison is made against single engine tests. Obviously the cost of these tests precludes duplication except where absolutely necessary, but borderline cases may have yielded results which would have improved the correlation.

Taking the general character of an engine test into consideration, therefore, the correlation can be regarded as satisfactory.

Recommended Form of Beaker-Corrosion Test Apparatus and Procedure.

Having regard to the results of the investigations and experience in developing the Beaker-Corrosion Test, it was considered necessary to make manipulation as convenient as possible and to ensure that a rapid change of specimens could easily be effected.

As a final modification therefore a more robust beaker cover was designed and cast from aluminium. In the following section a description is given of the apparatus in its final form, together with photographs and details of the procedure to be adopted.

Apparatus.

The apparatus shall consist of a Pyrex glass beaker fitted with a stirrer composed of the bearing-metal test-piece and covered with an aluminium cover (Fig. 7). Means shall be provided for maintaining the oil in the beakers at 160° C. The heating bath (Fig. 8) shall be constructed to hold four beakers and must provide an even distribution of heat to the beakers.

(a) *Beakers.*—Tall beakers of 1500 ml capacity with special flanges to support the aluminium cover.

(b) *Thermometers.*—I.P. low-distillation thermometers shall be used for both beakers and heating bath.

(c) *Beaker Covers.*—These shall be constructed of aluminium and be fitted with apertures to accommodate the thermometer, stirrer shaft, and copper catalyst. The cover shall be provided with slides over the stirrer-shaft aperture to facilitate removal of the test-pieces.

(d) *Heating Bath.*—The heating bath shall be such that four beakers can be immersed in the heating medium (*e.g.*, refined bright stock) to a depth of 3 in and the oil in the beakers maintained at a constant temperature. Details of the bath are as follows :—

Dimensions of Oil-bath.—10 × 23 × 5 in deep.

Stirring.—Two paddle stirrers situated 6½ in from each end of the bath. Diameter of paddles 2 in; speed of rotation 900 r.p.m.

Lagging.—Glass wool covered with tin-plate.

Source of Heat.—2 × 300-watt windings supported on porcelain insulators. The windings are arranged vertically, one along each of the longer sides of the bath. One element is coupled direct to the supply line, and the other is automatically controlled by means of a Sun-Vic thermostat (Type T.S.1).

The top of the bath is fitted with a well-fitting, lagged cover provided with holes for accommodating the beakers, the shafts of the paddle stirrers, the current leads, and the bath thermometers.

(e) *Test Specimen Shafts.*—¼-in steel rods, 12 in long fitted at top with pulley and threaded 2 BA. at the bottom to hold test-piece.

(f) *Test-pieces.*—The test-pieces shall be prepared from cadmium-nickel floating bushes (3 in O.D) by parting off ½-in rings in a lathe and sawing these rings into quadrants. Each piece shall be drilled centrally and tapped 2 BA.

(g) *Copper Catalysts.*—These shall consist of copper strips—6 × $\frac{5}{8}$ × approx $\frac{1}{32}$ in. A length of stout copper wire is brazed to the strip in order to facilitate positioning and removal from beaker.

Procedure.

(a) *Treatment of Test-pieces and Catalysts.*—Before use these shall be rubbed with a fresh strip of No. 0 emery cloth, washed with petroleum ether, and dried. The test-pieces shall be weighed to the nearest mg.

(b) *Assembly of Apparatus.*—The current to the bath windings is switched on and the oil in the bath allowed to heat up, with stirring, until its temperature is sufficient to maintain the oil under test at 160° C. A 2-in depth of the oil to be tested shall be placed in the beakers and the aluminium covers fitted to the beakers using pieces of asbestos string as packing under the beaker rims. They shall then be lowered into position through the large holes in the bath cover. The thermometers and test-specimen shafts shall then be inserted through the appropriate apertures in the aluminium covers, the catalyst apertures being closed by corks.

(c) *Test Procedure.*—As soon as the oil in the beakers has reached 160° C, the copper catalysts, bent as shown in Fig. 7, shall be inserted through the appropriate aperture in the cover and the prepared test-pieces screwed, concave face downwards, on the lower threaded end of the stirrer shaft. When assembly is complete, the beakers should be completely closed.

The stirrers shall then be rotated for about 1 min, stopped, and their positions adjusted so that the upper faces of the bearing specimens are just below the surface of the oil. Stirring at the correct rate (680 r.p.m.) shall then be commenced.

At intervals of 2 hr the paddles shall be stopped and the four copper catalysts removed and replaced by similar freshly prepared strips. The four bearing specimens shall be removed, washed, dried, and weighed at the same 2-hr intervals, but replaced by freshly prepared specimens every 4 hr.

(d) *Reporting of Results.*—Summations of the losses in weight of the bearing specimens at each progressive interval of time shall be made, and the resulting losses in weight plotted against time of treatment. From the curves so obtained, the times in hours required for losses in weight of 10, 100, and 500 mg to take place shall be read and recorded. To obtain a measure of the " breakdown time " of the oil, the linear portion of the curve shall be extrapolated downwards in a straight line to cut the horizontal axis and the point of intersection (in hours) shall be noted.

It is essential to carry out all tests in duplicate and preferably against reference oils whose behaviour in an engine is known.

Discussion.

The preliminary experiments with the Beaker-Corrosion Test showed that the method appeared basically suitable for the purposes required, that is, to place lubricating oils in their relative order as regards corrosive properties and to maintain the same order as that obtained by engine tests.

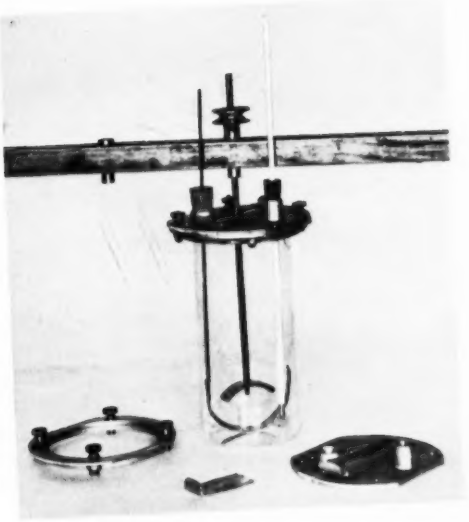

FIG. 7.
BEAKER FITTED WITH ALUMINIUM CLOSURE.

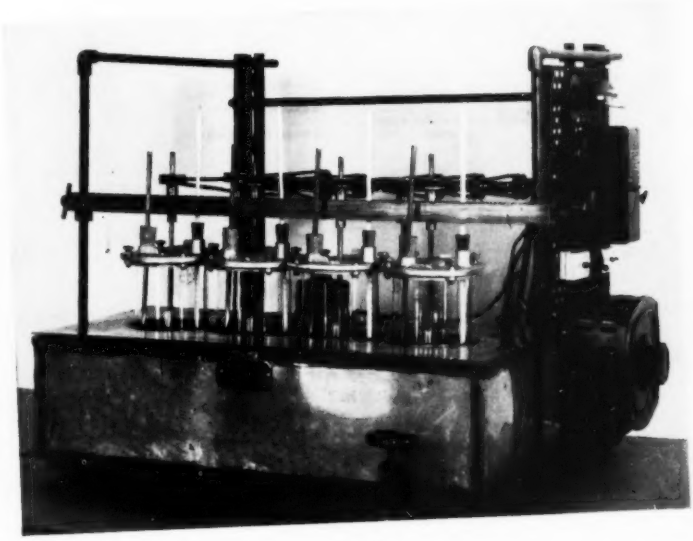

FIG. 8.
COMPLETE FOUR-BEAKER UNIT FOR BEAKER-CORROSION TEST.

[*To face p.* 450.

Differentiation between oils of different corrosive potentialities was sometimes very difficult, and the first step to improve the test was therefore to ensure better repeatability. In this connexion, the fact that " lacquering " of the metal surfaces was observed to occur during the test was considered. This was most noticeable with oils having non-corrosive properties or to which anti-corrosion inhibitors had been added. It appeared that this effect may have been responsible for the lack of repeatability in the original tests and also that, owing to its protective nature, the " lacquer " may have caused a false interpretation to be placed on the results of the test.

Again, it appeared unlikely that, under service conditions, such a lacquer could remain for any length of time on the bearing surfaces. It was therefore decided to remove this effect as far as practicable by renewing the metal surfaces presented to the oil at suitable intervals during the test.

On a corrosive oil the effect was small, from which it would be reasonable to assume that the oil was of a sufficiently corrosive nature to attack the metal before lacquer had time to form.

The effect of the surface-renewal procedure in improving repeatability is marked, four out of five oils giving results in close agreement. The failure of the fifth to yield duplicate results in reasonable agreement was obviously the next subject for experiment, and here the effect of the apparatus design is brought out conclusively in the work described on ventilation of the beaker.

This work showed that a measure of control over the escaping products of deterioration had already been functioning in the original apparatus, but that this needed some standardization. This was accomplished by careful selection of beakers and covers, thus removing the main cause of lack of repeatability in the test, *i.e.*, uncontrolled loss of volatile corrosive products of oil decomposition.

The effect of allowing the products of deterioration to escape at will, using corrosive oil A, presents interesting indications as to the cause of corrosion of bearing surfaces, since it would appear that if vapour could be carried away as soon as formed, little corrosion would occur. This means that the oil itself may not become inherently corrosive in reasonable service, but that the volatile products formed on deterioration are the main active agents in this respect.

The use of copper as a catalyst in this work followed naturally from the fact that this metal appears in one form or another in many parts of lubrication systems, and its catalytic effect is evident from a study of Fig. 4. This shows the results of experiments using no catalyst at all and also using catalysts of varying surface areas.

The response of the six oils examined to variations in catalyst area presents interesting features in that three of these show a linear relationship between surface area and breakdown time, whereas two show definite curves, whilst the remaining one shows a linear relationship until the surface area is much reduced.

This phenomenon somewhat complicated the search for the optimum area of catalyst, since it could not be predicted for an unknown oil what type of response would be likely to result. However, that chosen as optimum from the work carried out was confirmed by the success of subsequent work.

The effect of temperature on the test was found to proceed much according to expectations, and the temperature of 160° C, originally chosen, appeared to satisfy the optimum conditions for the test. This again was confirmed by subsequent work.

It became clear from the experimental work discussed, and as a result of experience in the examination of a large number of oils, that the test had been raised to a higher level than that of a simple " go-not-go " test, since the precision had been greatly improved and adequate differentiation between oils of different corrosive potentialities had been obtained. The actual precision data given show this clearly.

There remained now to consider these results in comparison with the engine-test data. The results of the Bristol single-cylinder Hercules test, by which the oils under consideration had been rated, were taken for this correlation.

As a basis for correlation, consideration was given to all aspects of both laboratory and engine tests, and it was soon evident that the " breakdown-time " results best served this purpose for the Beaker-Corrosion Test, and the " pass " or " fail " results for the Type II or III engine tests. Attempted correlation with actual engine-bearing weight losses did not yield any information of value in this work.

The final correlation, based on the results given in Table VII, showed that the behaviour of an oil in the Bristol engine could be predicted for 85·7 per cent of the oils examined in terms of " pass " or " fail " in either Type II or III test. The formula evolved for this prediction was used with considerable success during the recent war, and as a result much of the engine-testing became unnecessary. Only those oils rated as border-line cases were found to require the decision of the engine before being either passed or condemned as regards their suitability for use in aero engines.

The correlation discussed above was based in all but one case on single engine tests, and here it should be observed that had repeat engine-test results been available, the percentage of correct predictions from the Beaker-Corrosion Test results might have been higher.

It is realized that in its present form the test is suitable only for corrosion studies towards cadmium–nickel bearing metal, but only minor modifications should be necessary to permit other corrosion studies to be made, since the design of the apparatus is comparatively simple and allows of easy alteration.

Further studies on the corrosive potentialities of lubricating oil will necessarily involve some detailed research as to the influence of the fuel used, the effects of modern additives, and the conditions obtaining in modern engine design. It is hoped, therefore, that this paper may form a useful contribution to advancement in the pursuit of these studies.

Acknowledgments.

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Thanks are also due to the Ministry of Supply for permission to publish

the results of engine tests, using the Bristol single-cylinder Hercules engine, which were obtained during the war and used for correlation with the Beaker-Corrosion Test.

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